CARBON LIFE CYCLE ASSESSMENT OF SHELTERBELTS IN SASKATCHEWAN

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ABSTRACT

Shelterbelts are beneficial for protection against soil erosion, as well as for the promotion of biodiversity and wildlife habitat. Additionally, they play an integral role in carbon sequestration through growth in tree biomass and agricultural soil. The widespread adoption of shelterbelts was, in part, triggered by concerns about erosion of topsoil caused in the drought-prevalent years in the early to mid-20th century. In recent years, it has become more common to remove these shelterbelt trees to convert land to crop production or due to the increasing size of equipment imposing difficulty navigating around the shelterbelt during seeding, spraying, and harvest. In addition, soil erosion is no longer a risk due to wide spread conservation farming practices being employed.

Life Cycle Assessment (LCA) is a tool that observes and analyzes the entire life of a phenomenon from 'cradle to grave'. A Carbon-LCA of planted shelterbelts accounts for the processes by which carbon dioxide is sequestered through the function of photosynthesis by tree species and micro-organisms in agricultural soils as well as its emission produced during various life stages. The pan-Canadian framework outlined by federal government of Canada in 2018 has made a goal of a nation-wide carbon tax or cap and trade equivalent. There is likely potential for financial incentives to adopt management plans, which reduce one's carbon footprint.

There is a lack of information on the amount of carbon sequestered and emitted at each life cycle stage for the six common shelterbelt tree species (hybrid poplar, green ash, Manitoba maple, Scots pine, white spruce, and caragana) found in the Saskatchewan prairies. This study aims to estimate the net carbon sequestered by various tree species by various production stages.

Net amount of carbon sequestered was a sum of that emitted as well as sequestered. Overall analysis was divided into two major parts with the first being the carbon dioxide (CO_2) emissions for one year of seedling production, roughly 500,000 seedlings, was 1,100 tonnes (t), or 0.002 t per individual seedling. The second LCA stage, transportation a typical full shipment had CO_2 emissions of 6.08 t for delivery to Regina, SK from Estevan, SK. For shipments of the same number of seedlings to Saskatoon, SK and Prince Albert, SK, the emissions were 14.10 t and 17.20 t CO_2, respectively. Production of seedlings accounted for 95-98% of total emissions during this stage, depending on where the shipment was delivered. The highest emitters in the

production phase included electricity at roughly 83% (or 914.71 t CO_2) and heating at 11% (or 121.00 t CO_2).

The planting phase accounted for 1.90 t CO_2/1000 seedlings. Maintenance accounted for 0.49 t CO_2/1000 trees. These life stages added an insignificant amount of CO_2 emissions comparatively to the amount that a shelterbelt can sequester over its life. All of these emissions are balanced by carbon sequestered by trees and the soil. Each shelterbelt species sequestered a different rate of carbon, with hybrid poplar sequestering the most carbon in all three soil zone clusters selected for the study. Hybrid poplar is a rapid growing tree and subsequently sequesters the most carbon of the six species in all soil zones, with a km stretch of shelterbelt sequestering upwards of 1460 t CO_2 by age 60. Manitoba maple and white spruce are the next highest carbon sequesters. The final stage of the shelterbelts is its eventual disposal – assumed in this study to be their removal. This stage of removal boasted CO_2 emissions for two reasons: the physical process of removing the trees as well as the carbon lost due to burning of removed biomass. The removal of a km long shrub shelterbelt released 0.82 t CO_2. The removal of coniferous and deciduous trees in a shelterbelt equated 1.12 t CO_2. Removal of a shelterbelt of large sized hybrid poplars produces 2.43 t CO_2.

Keywords: Carbon sequestration, Life Cycle Assessment, Shelterbelt, Seedling Production, Carbon Pricing, Greenhouse gas emission

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LIST OF ABBREVIATIONS

3PG –Physiological Principles in Predicting Growth

AAFC – Agriculture and Agri-Food Canada

AGGP – Agriculture Greenhouse Gases Program

ALCA – Attributional Life Cycle Assessment

BMP – Beneficial Management Practice

BOD – Biochemical Oxygen Demand

CBM – CFS3 –Carbon Budget Model of the Canadian Forest Sector

CH_4 – Methane

CLCA – Consequential Life Cycle Assessment

CO_2 – Carbon Dioxide

CO_2eq – Carbon Dioxide Equivalent

DOM – Dead Organic Matter

DSS – Decision Support System

EIO –Economic Input-Output Analysis

GHG – Greenhouse Gases

IO – Input Output Analysis

ISO – International Standards Organization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LTCPF – Long-term Carbon Price Forecast

N_2O – Nitrous Oxide

NMVOV – Non-Methane Volatile Organic Carbon

OBPS –- Output Based Performance Standards

RBS – Randomized Branch Sampling

TEC – Total Ecosystem Carbon

USLCI – United States Life Cycle Inventory

CHAPTER 1: CARBON LIFE CYCLE ANALSYIS: INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction: Background Information/ Study Summary

Shelterbelts are rows of trees and shrub species representing the perimeter to many farmyards; they exist as transects in crop and pasture fields, and run adjacent to bodies of water, such as rivers and creeks. Shelterbelts became a popular agricultural management practice for Canadian prairies, including Saskatchewan, in the early 1900s. Prior to the 1960s, shelterbelts were established in uniform designs, bordering roadways during a time period that road infrastructure was widespread (Amichev et al., 2015). The main reasoning for the addition of trees and shrubs was to reduce soil erosion from cultivated fields as well as to reduce blowing dust from the roads. In the 1970s and 1980s, shelterbelts were planted at cross roads in an attempt to control the buildup of snow. The increase in overall use of field shelterbelts occurred in the 1990s and early 2000s (Amichev et al., 2015). In recent years, it has become more common to remove shelterbelts to convert land to crop or create more space for larger farming equipment (Rempel, 2014).

Shelterbelts are beneficial for many reasons. As already mentioned, they serve as protection against soil erosion from wind and water. Shelterbelts also promote biodiversity in the otherwise monoculture dominated landscapes of agriculture. Wildlife habitats, snow retention for moisture control, recreational opportunities, and aesthetic and bequest values are additional benefits provided by shelterbelts (Rempel, 2014). Shelterbelts also play a uniquely important environmental role of carbon sequestration, and are being pointed to as a climate change mitigation tool (Amichev et al., 2016a).

Amichev et al. (2015) have undertaken research, which was funded through the Agricultural Greenhouse Gases Program (AGGP), on the carbon sequestration potential of six common tree and shrub species used as shelterbelts in Saskatchewan. The research outlined the growth characteristics and estimated carbon stocks of five trees species, white spruce (*Picea glauca*), green ash (*Fraxinus pennsylvanica*), hybrid poplar (*Populus spp.*), Manitoba maple (*Acer negundo*), and Scots pine (*Pinus sylvestris*), and one shrub species, caragana (*Caragana arborescens*) (Amichev et al., 2015). In the first phase of this study (called AGGP1), over a 5-year period, several areas were studied, including: shelterbelt inventory techniques; biomass growth and carbon pools/fluxes; radial tree growth; the effects of future climate change scenarios on carbon sequestration; environmental and economic benefits of adopting shelterbelts; carbon monitoring of shelterbelts in field; and shelterbelt design (see Amadi, 2016; Amadi et al., 2016; Amichev et al., 2016b; and Wiseman et al., 2009). Although carbon sequestration levels by trees were estimated, other activities related to shelterbelt system were not included. This study was designed to fill this void by taking a total spectrum of carbon sequestration resulting from a shelterbelt system.

1.2 Purpose and Objectives

The purpose of this research is to delineate various stages for common planted shelterbelt species in Saskatchewan in order to estimate their net CO_2 balance. In addition, the trends in carbon pricing are also reviewed in order to establish the financial worth of adopting and retaining shelterbelts based on their CO_2 sequestration and storage capabilities.

The purpose of this chapter is to provide background and literature review on relevant information regarding LCAs, the current trends in carbon pricing both in Canada and globally, as well as beneficial management practices (BMPs).

The objectives of this chapter are to provide background and literature review on: (a) Life Cycle Assessments (LCA); (b) Carbon pricing and policy globally and within Canada, and, (c) Beneficial Management Practices (BMPs).

1.3 Literature Review

1.3.1 Introduction

The literature review was undertaken to provide a basis for understanding the key components of carbon life cycle assessment (LCA) of planted shelterbelt trees. The review focuses on the explanation of the life cycle assessment, including the phases involved in this framework, the different types of LCAs, application techniques, challenges and data and tools of LCAs. Within this review, the specific LCA method used in the research, LCI Select, is also outlined. A brief overview of how these estimates generated by the LCA are relevant from an economic standpoint is also presented. This is followed by information on BMPs as they pertain to the planted shelterbelts, and then by concluding comments.

1.3.2 Life Cycle Assessments (LCAs)

The International Organization for Standardization (ISO) defines LCA as "the compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006, p. 2). The creation of LCA was mainly to advise development of goods and services, and furthermore, to instruct policies. Use of LCA has supported the groundwork for bottom-up approaches in planning and management (Rajagopal et al., 2017). According to Finnveden et al. (2009), the LCAs have a comprehensive scope, which is helpful in avoiding problem-shifting (e.g., among different life-cycle phases, among different regions affected by the life cycle under review, and among different environmental problems).

LCA results can create incentive for developers to innovate sustainability (Zilberman et al., 2012). They can be used to assess and note how much greenhouse gas[1] (GHG) emissions are being emitted during the life of a product or service. The atmospheric levels of these gases have increased significantly since the industrial revolution, due to anthropogenic activities (Watson et al., 1990). LCA-based result can be used to develop regulations for a given GHG emitting sector. For example, LCAs assessed GHGs can be observed in the Low Carbon Fuel Standard (LCFS)

[1] The GHGs include: carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), nitrogen trifluoride (NF_3), nitrous oxide (N_2O), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) (Government of Canada, 2018).

regulation in California, which sanctions a reduction in the life-cycle GHG severity of fuels used for transportation within the state boundaries. This creates an incentive for innovation in cleaner, more efficient technologies, such as biofuels and electric vehicles (Government of California, 2017b, and Rajagopal et al., 2017).

There are four phases in undertaking a LCA study: 1) Goal and Scope Definition; 2) Life Cycle Inventory Analysis (LCI); 3) Life Cycle Impact Assessment (LCIA); and 4) Interpretation (Finnveden et al., 2009). The Goal and Scope Definition phase covers the reasons for undertaking the study, its planned use, and the intended audience (ISO, 2006). It is also where the system boundaries for a given study and functional unit(s) are addressed. The functional unit denote the quantitative measure of the functions provided by the product or service under study. The LCI is a collection of the inputs (i.e., resources) and the outputs (i.e., emissions) from the good throughout its life cycle relative to the functional unit. The LCIA is used to discern and measure the importance of the possible environmental impacts of the system under study (ISO, 2006). It is important to note a limitation of this method under the ISO approach — that LCIA is restricted to the environmental impacts and do not address the other two pillars of sustainability — economic and social (Hunkeler and Rebitzer, 2005). In the Interpretation phase, the assessment of results of previous phases, related to the goal and scope, is completed, so that conclusions and recommendations can be made (Finnveden et al., 2009; ISO, 2006; Strazza et al., 2013).

1.3.2.1 Attributional LCA vs. Consequential LCA

There are two main types of LCAs distinguished within the literature — Attributional Life Cycle Assessment (ALCA) and Consequential Life Cycle Assessment (CLCA)**.**

The ALCA is the earlier form of LCA and focuses on tracking and predicting emissions associated with each stage in the “cradle to grave” timeline. It is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle system and its subsystems (Curran et al., 2005). ALCAs can be used to make comparisons of life cycle emissions of similar products (Rajagopal et al., 2017). However, ALCAs should be used as a broadly applied method (Finnveden et al., 2009), as such studies consistently use average data (Finnveden et al., 2009).

CLCA is used as a tool for decision-making (Finnveden et al., 2009), as it assesses the total emission change because of a decision (e.g., change in policy) (Rajagopal et al., 2017), and is therefore environmentally relevant (Curran et al., 2005). The expansion of system boundaries, to involve outside effects of the LCA system is fundamental part of a CLCA (Ekvall and Weidema, 2004). In contrast to the ALCAs, the CLCA studies most often use marginal data (Finnveden et al., 2009). CLCAs tend to consolidate economic approaches, including marginal costs and data and market-mediated effects (Ekvall and Weidema, 2004).

Although ALCA and CLCA approaches have different functions, Rajagopal (2014) states that they are complimentary and both have relevance in policy formulation. Estimated yields from ALCA emissions from a single polluter can be used to establish if a good is in compliance of a standardized target. The CLCA can provide policy makers a comprehensive look at the environmental impacts or decision-related consequences of a policy (Rajagopal et al., 2017).

For the purpose of this study, an LCA being more representative of an ALCA is utilized, as the goal of the study was to outline the net carbon sequestered and stored, as well as lost during the removal phase, of shelterbelt shrub and tree species. The goal of this study is not to make decisions regarding changes made to the process of production, transportation, planting and maintenance of seedlings/trees, but rather to outline them in order to understand the comprehensive exchange of carbon throughout all life cycle stages. Suggestions, however, on how emissions in these areas may be reduced are included in concluding statements.

1.3.2.2 Economic Input-Output, Conventional LCA, and Hybrid Techniques

Techniques are the processes by which the LCAs, whether attributional or consequential, are applied. There are two commonly discussed techniques of LCAs: Conventional LCA and Economic Input-Output Analysis (EIO).

The Input–Output Analysis (IO) exists in the economic field and makes connections between industries and households in a national economy in the form of “supply and consumption of goods and services, formation of capital, and exchange of income and labour” (Finnveden et al., 2009, pg. 7). A concern with IO based LCA is that the resolution of a sector is too unrefined for dominant LCA applications (e.g., raw material selection and process redesign) (Finnveden et al., 2009).

A conventional LCA considers the primary inputs (e.g., fossil fuels), the interactions following suit, the environmental burdens (e.g., air emissions – GHG pollution), as well as the expected output of the system with which the product or service exists (Rajagopal et al., 2017). Lave et al. (1995) stated that conventional process-LCAs could fail to acknowledge considerable components of environmental aspects in the LCI (Life Cycle Inventory) Analysis, specifically when the majority of environmental emissions are taking place in upstream processes (Lenzen, 2000). This issue results from process-LCAs being unable to include all processes (Finnveden et al., 2009).

Hybrid Technique involves combining the advantages of both conventional LCA and IO-LCA has been suggested as a means to address the limitations of both approaches (Suh et al., 2004). This combination of approaches is referred to as the "tiered-hybrid approach" (Finnveden et al., 2009). Moriguchi et al. (1993) established the practicality of the "tiered-hybrid approach", and analyzed the core processes using the conventional LCA technique, then estimated the upstream flows connected to the core processes, using the IO technique.

The research on the carbon life cycle assessment of shelterbelt trees and shrubs is most similar to that of a conventional LCA, as it involves a basic investigation of the major greenhouse gas — carbon dioxide, being emitted during various life cycle stages, as well as the amount of carbon stored by the shelterbelt.

1.3.3 Other LCA Challenges

LCAs include both methodological and implementation-related challenges. Methodological challenges may include modeling emissions due to price effects; system boundary selection; joint production; and variability and uncertainty. Implementation-related challenges involve a lack of confidence in life cycle assessment as a tool and its consequences; mitigating emissions due to price effects; inadequate choice of alternatives; communication and engagement or practitioners, policy makers, and other stakeholders throughout the life cycle assessment process; the policy-making process and the cost of life cycle assessment (Rajagopal et al., 2017).

The challenge of variability and uncertainty are applicable in this study, as they are in any LCA. In areas where data gaps exist, the use of proxies may be used, which may affect the reliability of the research. Additionally, inputs values may differ case by case as there is a level of variability between producers and landowners in their approach to management, which can impact the emissions associated with various life stages.

1.3.4 Data and Tools for LCAs

LCAs are data intensive. International, national and regional databases have been created, although the majority are relatively new (established in the last few decades) to provide inventory data on a variety of products and services (Finnveden et al., 2009). Various national and international public databases have been previously released (for examples, see CPM, 2007; Ecoinvent, 2007; European Commission, 2007; JEMAI, 2007; Narita et al., 2004; NREL, 2004; RMIT, 2007; UBA, 2007).

Some databases provide data modules used in inventory building on a disaggregated level (i.e., per production step, where each input and output is recorded in addition to aggregated sets of data). Other databases provide inventory data in an already-aggregated format, which indicate the basic aggregated flows of all processes. Aggregated data are more readily available, reliable and representative. However, despite company confidentiality being guaranteed in aggregated data, it is argued to potentially have hidden biases and lack transparency to some extent (Finnveden et al., 2009). Unit process data refers to particular technology which allows for custom inventories, selection of technology that are present in the scenario being investigated and allows for more specific study focus (Finnveden et al., 2009).

The LCA tool in this study is SimaPro, which is a LCA software program that is utilized in both the fields of academia and industry. It is used to quantify the environmental impacts that products and services have based on their complete life cycle, which begins at the initial stage of production, to transportation of goods, its use phase, and its eventual disposal including removal, and subsequent uses. SimaPro has been utilized for decisions in policy-making regarding the environment (SimaPro, 2019). SimaPro has access to a number of life cycle inventory databases, which contain information on a wide variety of products and processes and their respective environmental impacts. For the purpose of this study, EcoInvent was utilized for data retrieval on the inputs required in the life cycle phases. EcoInvent contains thousands of records of well-documented process data, and considered the life cycle assessment stages. The database has over 10,000 data sets, which cover a number of sectors such as agriculture, energy and manufacturing (EcoInvent, n.d.).

SimaPro has a variety of impact assessment methods, which are available to calculate the impact assessment results of the product of service in question. These include: Characterization, damage assessment, normalization, and weighting (PRé, 2019).

LCI Selected Results is a method within SimaPro that outlines the sum of environmental indicators emitted to a compartment and therefore combines the emissions to different sub-compartments. Indicators include: land occupation, water, carbon (biogenic, fixed), carbon monoxide, CO_2 (fossil), lead, methane, N_2O, nitrogen oxides, NMVOV (non-methane volatile organic carbon), particulates, Sulphur dioxide, zinc, cadmium, etc. (Frischknecht and Jungbluth, 2007).

1.3.5 Review of Similar Studies on Life Cycle Assessments

1.3.5.1 Ornamental Tree Nursery in California, United States

Kendall and McPherson (2011) conducted a study on the life cycle greenhouse gas inventory of an ornamental tree production system based in California, USA. The scope of their research covered the cradle-to-retailer concept. This inventory included input costs (materials and chemicals), electricity and fuel use, and the transportation of inputs and products of a tree nursery and its suppliers for the production of a 5-gallon sized tree. This value refers to the weight of the tree and soil plug attached. The production phase for the said tree was just over four years in time. It is important to note that the production time of ornamental trees often takes much longer than seedlings produced for forestry/agriculture. The study focused on Monrovia Nursery, which provided data on the fuel and electricity, the production activities applied, greenhouse emissions, irrigation and different buildings costs (Kendall and McPherson, 2011). Most of the information was analyzed through the LCA software tool GaBi and databases. The transportation and equipment fuels, such as diesel and gasoline use for the nursery trucks, tractors and other equipment, were included in the study. The United States Life Cycle Inventory

(USLCI) database was used for this data and reported using GaBi (Kendall and McPherson, 2011).

The main categories for emissions for the production of a 5-gallon tree were energy use on site, materials, and material transport. Direct energy use, i.e., fuel and electricity used on-site was the largest source of emissions at approximately 44% of total CO_2 produced, with irrigation and radiant heating requiring the most energy of the separate categories. The production of the material inputs required in the nursery operation was the second most impactful source of CO_2 emissions at 36% of the total. Transport of materials ended up being 16% of the overall GHG emissions with the largest transport cost being the bamboo stakes shipped from China. The emissions caused by diesel used to transport the fuel required by the nursery attributed to 32% of the emissions related to transport. The remaining 4% of emissions came from N_2O from the potting mix and fertilizer used (Kendall and McPherson, 2011).

A 5-gallon tree within urban forestry settings typically amounts to an emission production of 4.6 kg CO_2 equivalents (CO_2e) (Kendall and McPherson, 2011). Kendall and McPherson (2011) note that the emissions of ornamental trees are an additional 100 times higher than the seedlings used for forestry or agroforestry operations. Non-ornamental seedlings emissions were estimated at 0.029-0.133kg CO_2e per seedling (CORRIM Inc., 2004; Aldentum, 2002) due to longer growing time (four to five years) at the nursery. Comparing this data to the amount of carbon sequestered by urban trees in three cities in California (Sacramento County, Modesto, and Santa Monica), it was concluded that the CO_2 emissions rates during the production phase equated 20% to 50% of the mean annual carbon capacity (Kendall and McPherson, 2011).

1.3.5.2 Field-grown Red Maple Trees in Midwestern United States

Ingram (2012) analyzed field-grown maple trees in the lower Midwestern region of the United States using LCA. The objective of this study was to quantify the environmental impact, specifically the carbon footprint, of the production phase overall and the distinct steps within this production stage. The scope included the use and end-of-life stages. The product focused on a 6-cm diameter *Acer rubrum* “October Glory” tree (American Nursery and Landscape Association, 2004). The inputs required for the production included sand, root-inducing substance, fungicides and insecticides, mist pump, fertilizer, and equipment. Fertilizers and equipment use have been pointed out to be significant emitters of GHGs (Lal, 2004; Nemecek et al., 2005). Once trees were harvested, they were graded and stored in an unheated barn prior to being loaded and transported for their final use (Ingram, 2012). The sequestration that occurred during the production phase was calculated from the mean dry weights of the trees and projected using a growth model of the finished product (Center-for-Urban-Forest-Research, 2008).

Results of this study showed that the 5-cm diameter of the red maple tree in mid-western U.S. had a net carbon footprint of 0.840 kg CO_2e (including carbon sequestered during this phase) up until the point of the tree leaving the nursery. Transportation and transplanting boasted an additional 7.373 kg CO_2e, with the total cutting-to-landscape carbon footprint being around 8.213 kg of CO_2e per tree. Input materials and equipment use between the two nurseries accounted for 12.11 kg CO_2e/tree. Field machinery alone attributed 9.25 kg CO_2e/tree. The general operations of the nursery (e.g., electricity and gasoline consumption) equated 1.09 kg CO_2e/tree in the two nurseries. Fertilizer and pesticides accounted for 0.10 kg and 0.02 kg of CO_2e, respectively (Ingram, 2012).

It was estimated that trees would emit a total of 11.88 kg CO_2 per tree over the four years of production. Using a method used by the U.S. Department of Energy (USDOE) (1998), the estimated total CO_2 sequestered during the field production stage was calculated to be 20.60 kg CO_2/red maple tree for a 4-year production cycle (Ingram, 2012). If transplanted into a favorable environment, life-time level of carbon storage (in GWP terms) for the red maple tree was 901 kg CO_2. Of this value, 95% was observed in the first 50 years that the tree is in the field (Ingram, 2012). Considering the production, transplanting, use and end-of-life phases, the net positive impact of the tree on GHG production was projected to be 800 kg CO_2, which is 97 times more than the collective CO_2 emissions, including the production, transport and transplanting phases. Long-term storage in the roots remaining in the soil during end-of-life (death or removal) of the tree accounted for the 80% of carbon stored by roots, which is a stable sink. Applying this knowledge to the model, a minimum of 500 kg CO_2 is sequestered in the roots in the time span of 60 years. This stored carbon will remain in the rhizosphere past the 100-year assessment scope, given that the land is not tilled (Ingram, 2012).

1.3.5.3 Research Relevance

Both of the studies presented above conducted comprehensive LCAs on the carbon/carbon dioxide equivalents, throughout different life cycle stages of ornamental (Kendall and McPherson, 2011) and field (Ingram, 2012) trees. These studies are relevant to this study as they display the outline of stages of production, transport, and use. The removal stage (end of life) was not included in these studies. However, by looking at the separate life cycle stages, one can identify which processes are the highest emitters of CO_2. As it relates to the present study, the review is relevant since it can suggest the nature of analysis to be employed.

1.3.6 Carbon Pricing

Carbon pricing is attaching a cost to the emissions of CO_2, usually as expressed in tonnes CO_2. Globally, carbon pricing has become an increasingly popular tool in the past decade. The most common and comprehensive form of carbon pricing is to establish a tax on CO_2 emissions. Carbon pricing has been acknowledged as one of the more effective, transparent, and efficient policy approaches in reducing and mitigating greenhouse gas (GHG) emissions (Government of Canada, 2017a). Some form of mandatory pricing system, whether it exists or planned, has been implemented in every continent, save for Antarctica, as shown in Figure 1.1.

1.3.6.1 Carbon Pricing in Other Countries

Carbon pricing is occurring in a number of regions globally and particularly in countries such as Sweden, Switzerland and Liechtenstein, Finland, Norway, and France. These countries have the highest rate of carbon taxes (roughly \$168/t CO_2, \$127/t CO_2, \$93/t CO_2, \$78/t CO_2, and \$66/t CO_2, respectively) (World Bank Group, 2019). There are many countries that have planned or launched less ambitious goals, and the associated lower taxation rates, regarding carbon pricing and management, similar to the current status in Canada. In order to be consistent with the 2016 Paris Agreement temperature target, a minimum price range of \$53 to \$106 CAD per tonne CO_2 by 2020 is required (World Bank Group, 2019). A closer look at three different carbon pricing approaches is provided below for some contexts to illustrate of the variances that exist from place to place.

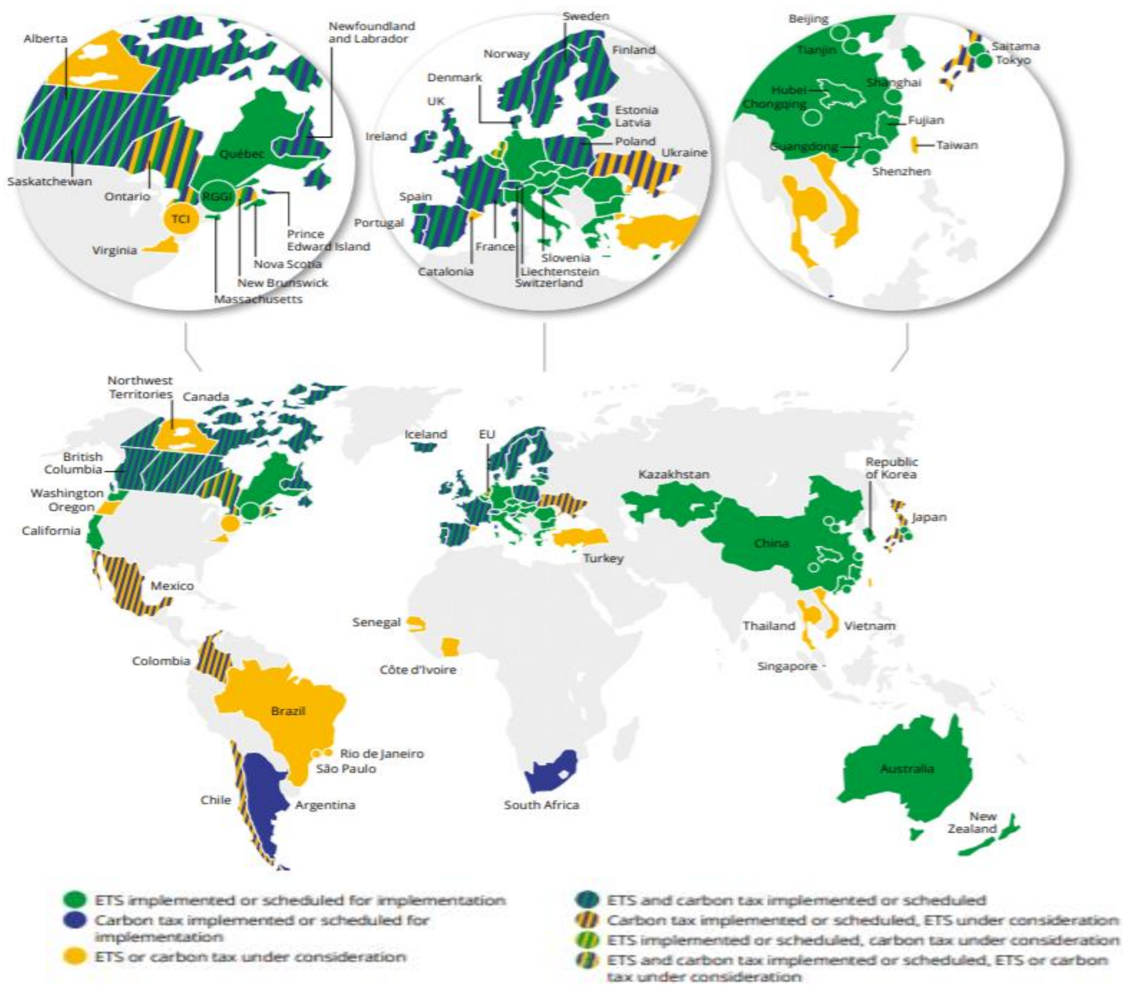


Figure 1.1 - Carbon Pricing and ETS Globally (World Bank, 2019)

The United Kingdom has had a carbon floor price (CFP) since its introduction by the Coalition Government in 2010. A CFP places a price on GHG emissions and requires heavy energy users to obtain permits, called "emission allowances", for each unit of GHG the user emits. According to the Climate Change Levy, the target price for 2020 was to be £30/t CO_2, with the initial price at £16/t CO_2 (Seely and Ares, 2016). However, in the 2014 budget, the UK government capped the floor price at a maximum of £18/t CO_2 from 2016 until 2020, which was eventually extended to 2021. The reasoning for this reduced goal was to limit competitive disadvantages for businesses and reduce energy bills for the consumer (Ares and Delebarre, 2016).

Australia adopted a carbon tax of AUS$23/t CO_2 in 2012 (Meng et al., 2012); however due to a lack of comprehensive support, the 2013 elected Federal Government put forward a package of seven carbon tax repeal bills (Department of the Environment and Energy, 2014). As of 2014, no new proposed carbon taxes exist in Australia; however, an Emissions Reduction Fund (ERF) with a safeguard mechanism was launched in 2016 in order to address the reduction of emissions in the coming years (Department of the Environment and Energy, 2017a). On March 7, 2019, the Australian Government amended the ERF Safeguard Mechanism. This involved a few changes to the Safeguard Mechanism, such as updating baselines, lowering administrative costs by simplifying the calculations of baselines (via the utilization of default values and prescribed production variables), and updating baselines on an annual basis for more accurate reflection of production (Department of the Environment and Energy, 2017b). The Australian government announced the Climate Solutions Package on February 25th, 2019, which is a CAD$1.83 billion investment to achieve Australia's nationally determined contribution (World Bank Group, 2019).

California chose a cap-and-trade style program over a carbon tax to assign a price to emissions, for its "firm limit on emissions, flexibility for business, and political feasibility" (Balmes, 2014). California uses a carbon capture and storage (CCS) program where CO_2 is either captured or removed from large industrial sources. Following this, it is compressed, transported and injected into the land subsurface in order to act as either a permanent or a long-term sink (Government of California, 2017a). The current price of carbon is CAD$21.30/t CO_2). The California cap-and-trade program has a post-2020 reform in place which includes an allowance price containment reserve and price ceiling which increases each year, projected to be US$94/t$CO_2$e in 2030 (World Bank Group, 2019).

1.3.6.2 Carbon Pricing in Canada

The Government of Canada outlined a benchmark for carbon emission pricing beginning in 2018. This was put in place to assure carbon pricing be applied to a wide range of emission sources throughout the country, and an increase in rigorousness via a rising price or declining cap over future years (Government of Canada, 2017a). Provinces and territories have flexibility to implement policies, which are adapted to their specific position that will meet the federal target of emission reduction (Government of Canada, 2017a). The federal government declared a nation-wide carbon price of \$10/t CO_2 in 2018 and \$20/t CO_2 in 2019 rising to \$50/t CO_2 by 2022 (Government of Canada, 2017a). In 2019, the federal backstop system was imposed on all provinces who did not meet the federal benchmark. The four provinces who did not meet the benchmark for carbon taxes or emissions trading systems (ETS) included Manitoba, New Brunswick, Ontario and Saskatchewan (Figure 1.2).

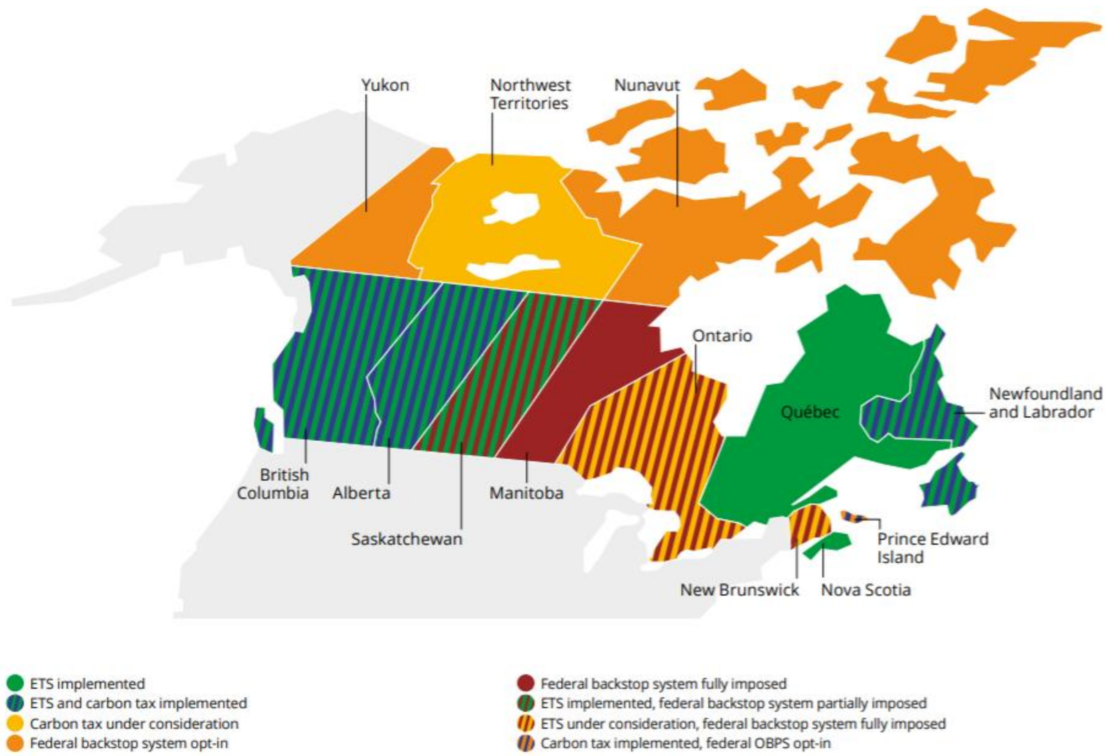


Figure 1.2 - State and Trends of Carbon Pricing – Carbon taxes and Emission Trading System (ETS) in Canada (World Bank, 2019)

A carbon tax has existed in British Columbia since 2008, which reached a level of \$30/t CO_2 in 2012, covering roughly three quarters of all provincial GHG emissions (Murray and Rivers, 2015). By 2015, the carbon tax was credited with reducing emissions by 5% to 15% since its implementation (Murray and Rivers, 2015). When the tax was implemented, no exemptions for specific sectors were outlined; however, in the 2014 budget, the Government of B.C. declared that gasoline and diesel used for agricultural production would be exempt from the carbon tax (Rivers and Schaufele, 2015).

Alberta has a hybrid system that combines a carbon levy with a performance-based system. The performance-based system exists under an output-based allocation system, where a party can receive performance credits if their GHG emissions are lower than the permitted level. If emissions exceed the amount allotted, some level of compliance will be required. Types of compliances include making a facility more efficient to reduce emissions, purchasing performance credits from those who did not exceed the limit, or donating to the Alberta's Climate Change and Emissions Management Fund (Government of Alberta, 2017a). In 2015, Albertans were paying an exceedance fee, meaning only the emissions rates, which exceeded the intensity target, were paid, of \$15/t CO_2 (Murray and Rivers, 2015). The province has outlined a carbon levy, where the tax is applied to all fuel emitting GHG emissions, of \$20/t CO_2 in 2017, and rise to \$30/t CO_2 in 2018 (Government of Alberta, 2017b). Similar to B.C., agricultural related fuel costs are exempt and energy efficiency programs exist for Albertan farmers (Government of Alberta, 2017b).

On January 1, 2019, Saskatchewan applied a baseline-and-credit ETS as part of the province's *Prairie Resilience Climate Change strategy*. The Output Based Performance Standards (OBPS) of the province accounts for the industrial facilities which emit more than 25 kt CO_2e and a voluntary opt-in for those who produce between 10-25 kt CO_2e (Saskatchewan Gazette, 2018). The Saskatchewan OBPS only partially met the federal benchmark and therefore the province was subject to the federal imposition of a carbon tax to account for emissions caused in the electricity generation and natural gas transmissions pipeline facilities. The province is currently challenging the Federal government's constitutional right of the enactment of the backstop in court (Government of Saskatchewan, 2018).

Manitoba put forward an intention to implement a provincial carbon tax; however, it did not meet the federal benchmark (Government of Manitoba, 2018). The province is challenging the federal backstop carbon tax, arguing that the provincial efforts consisted of a plausible GHG reduction plan (Government of Manitoba, 2019).

The provinces of Quebec and Ontario have separate but similar cap-and-trade systems. The "cap" component of this approach limits the amount (in tonnes) of GHG emissions that businesses and institutions can emit, with the "cap" lowering each year. In order to lower their emissions, industries will need to either "invest in clean technology, switch to lower carbon fuels, or purchase additional carbon credits". The "trade" component allows industries to buy and sell credits, meaning a company that reduced its emissions could sell to a company that is exceeding its cap (Government of Ontario, 2017). ICF Consulting (2017) released a *Long-Term Carbon Price Forecast Report* to the Ontario Energy Board outlining a forecast of carbon pricing. This report noted that a minimum long-term carbon price forecast (LTCPF) would equate \$17/t CO_2 in 2017, reaching \$27/t CO_2 by 2028. The maximum LTCPF would have to rise to \$67/t CO_2 in 2018, and may have to reach to \$108/t CO_2 by 2028 (ICF Consulting, 2017).

The Canadian government has outlined new actions it plans to take regarding carbon emissions from electricity, the built environment, transportation, industry, forestry, and agriculture and waste sectors. The approaches outlined for the forestry and agriculture include: (1) increasing carbon storage within forests and agricultural lands; (2) increasing use of wood for construction; (3) creating fuel using bioenergy and bio-products; and (4) advancing innovation (Government of Canada, 2017a). Some suggestions such as *The Pan-Canadian Framework on Clean Growth and Climate Change* provides for enhancing carbon sinks in agricultural lands include "planting more trees, improving forest carbon management practices, and increasing adoption of land management practices" (Government of Canada, 2017a).

1.3.6.3 Research Relevance

It is important to understand the current nature and future of carbon pricing within both Canada and other regions in order to assess the potential methods of a carbon pricing system to be implemented in Saskatchewan. It should be noted that these studies valuing carbon are not based on the damage caused by climate change; nor are they based on a feasibility analysis of various GHG mitigation options or ability of energy users to pay. Additionally, outlining the predicted cost of CO_2 production by year is key information to be applied to any programs, which provide incentives for carbon reduction management plans on agricultural land, including measures such as planting and retaining shelterbelts. Currently there is no proposed programs for incentivizing shelterbelts for their carbon sequestration potential within Saskatchewan.

1.3.7 Beneficial Management Practices (BMPs) in Saskatchewan

Beneficial Management Practices (BMPs) have been defined as agricultural management practices that can increase the sustainability of land and water source resources, benefit long-term economic and environmental growth, as well as reduce negative effects on the environment (Government of Saskatchewan, 2017). The Saskatchewan Farm Stewardship Program currently includes a cost-share incentive for landowners for a shelterbelt establishment. The intent of this BMP is "to provide assistance to plant trees and shrubs for protection of livestock facilities, snow trapping/field enhancement and vegetative buffers along riparian areas" (Farm Stewardship Program, 2016). Within this program, landowners are able to apply for a cost-share rebate of $1,200 per mile of shelterbelt trees up to a maximum of $5,000 given that they meet the basic eligibility criteria[2] (Farm Stewardship Program, 2016). The adoption and retention of shelterbelts on agricultural land is a type of BMP as it offers a variety of environmental benefits to the producer and land, with increased carbon sequestration and storage being one of major social benefits.

1.3.8 Knowledge Gap

There is currently no LCA study on the six Saskatchewan tree and shrub shelterbelts species that AGGP has outlined in their research scope. Data for the biomass and carbon stocks have been collected by the AGGP team for the six common shelterbelt species; however, the levels of carbon sequestered and emitted at each life cycle stage (production, transportation, use and disposal) have not been estimated.

The federal government has issued a goal of a carbon tax of $10/ tonne CO_2 emitted, or a cap and trade equivalent for 2018; however the economic predictions for carbon sequestering and storage efforts have not been identified for a Saskatchewan context. Currently no reward system for carbon sequestration has been outlined within Saskatchewan. However, an effective reward system may require information on the CO_2 emissions and sequestration by shelterbelts.

[2] Eligibility requirements: be a Saskatchewan producer or First Nations Band; be 18 years of age or older; file income tax, proving a minimum of $50,000 in gross farm income for the year of application or the year previous; producers who own, lease or rent property which contains livestock and poultry require a Saskatchewan Premises Identification (PID) number (Farm Stewardship Program, 2016).

This study aims to supplement the required information for potential future programs related to carbon credit.

1.4 Methods

1.4.1 Research Objectives and Methods

The objectives are:

Objective 1: Outline Carbon-LCA for the six shelterbelt tree and shrub species.

Method 1: To analyze the carbon stocks and biomass values utilizing existing data that were collected by AGGP1 field seasons;

Objective 2: Collect data on five LCA stages (Production, Transportation, Planting and Maintenance, Life in Field and eventual Removal);

Method 2: Perform interviews with stakeholders in these different LCA stages;

Objective 3: Complete full LCA for six shelterbelt species in Saskatchewan.

Method 3: Utilizing data from Objectives 1 and 2 as well as LCA software program SimaPro. With this data, economic importance of carbon sequestration was outlined based on trends in current carbon pricing.

1.4.2 Tasks Associated with Various Methods

1.4.2.1 Identification of Carbon Life Cycle Stages for Shelterbelts

The levels of carbon in its atmospheric form (CO_2) that are emitted during various phases of a shelterbelt system were quantified to understand the environmental costs of producing and using them. Figure 1.3 shows the system boundary for the life cycle stages included in this study. The different life cycle stages are denoted by their grouping and color in Figure 1.3. Additionally the plus and minus signs indicate whether the life cycle stage is responsible for the production or sequestration of CO_2 or other GHGs. The carbon sequestration occurs in the Life in Field phase, whereby CO_2 is sequestered as carbon in the tree's biomass, dead organic matter (DOM) – meaning the soil, roots, and leaf litter, and the total ecosystem carbon (TEC).

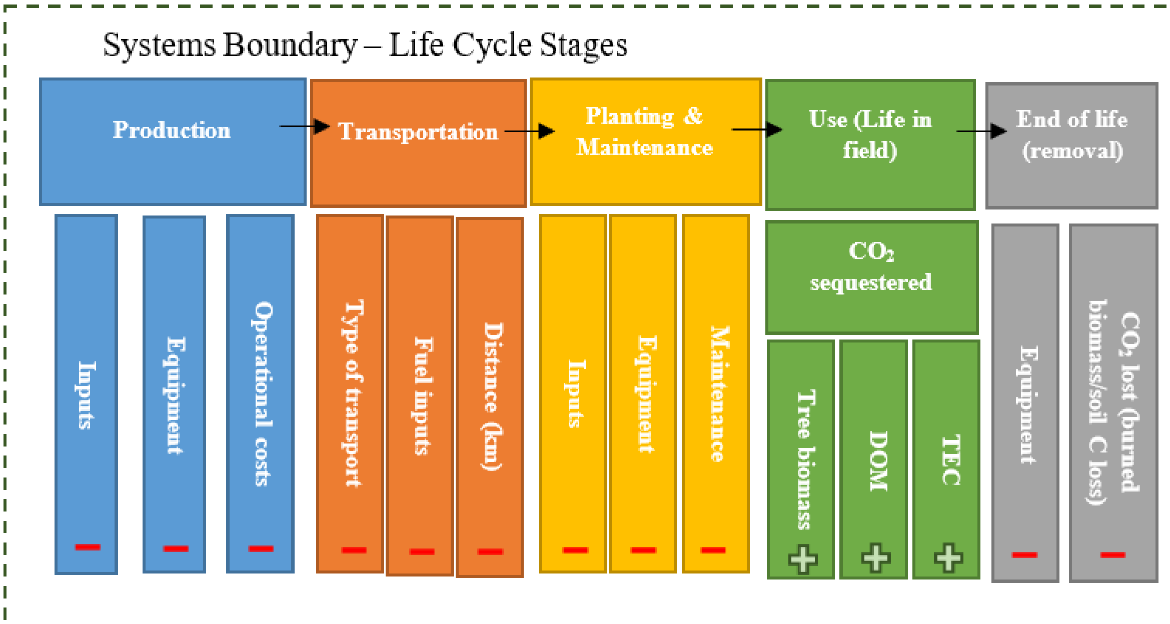


Figure 1.3 - System Boundary for Life Cycle Stages for LCA of Saskatchewan Shelterbelts

In order to assess the production phase of the shelterbelts, it is necessary to outline all of the production requirements of a standard tree nursery. The assessment of production should include all the input materials used including seeds, agricultural chemicals (fertilizers, herbicides, and pesticides), plastic tarps, and agricultural equipment (irrigation systems, chisel plows, turning plow, etc.). The transportation costs should include the distance that the tree seedlings travel from the nursery to a distributor, or directly to their final destination where they would be planted. The life stage of site preparation and planting should include the emissions caused by the farm equipment (tractor, tree planter, etc.), and any additional material used, such as plastic mulch. The potential sources of emissions for the management stages should be inclusive of farm equipment/gardening equipment (lawn mowing, trimming, irrigation, chemical application, etc.). The removal phase similarly should include the emissions caused by the equipment required (backhoes, bulldozers, track-hoes, etc.) as well as the carbon lost due to burning of the shelterbelt biomass. In this study, these data were collected by researching similar studies and pre-existing data values of carbon lost throughout these activities. This study also included contacts with currently operating tree nurseries, such as the SaskPower's Shand Greenhouse (located in Estevan, SK), and University of Saskatchewan greenhouses. From this former nursery, data on their operational costs were requested. An inventory was compiled to outline all of the carbon costs during the operation of a nursery and production of tree seedlings. These data and information were used in the LCA software program, SimaPro, to estimate the level of carbon footprint of shelterbelts.

The carbon that is sequestered throughout the life of the tree and shrub species was quantified using estimates by Amichev et al. (2016a). The biomass and carbon stock values were collected for each of the species at different ages. Amichev et al. (2016a) calculated the total carbon stocks for the six different tree and shrub species using the Physiological Principles in Predicting Growth (3PG) Model and the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). This information showed the rate at which carbon has been sequestered based on the biomass and growth rate of the trees. The 3PG model utilized climatological data (monthly maximum and minimum average air temperatures, vapor pressure deficit, precipitation, solar radiation, and the average days per month of rain or frost) in the time span of 1954 to 2014. The CBM-CFS3 model required only the mean annual temperature. The two models also incorporated soils data (soil texture, mean minimum, average and maximum water holding capacity in the soil, and soil organic carbon) and shelterbelt field data. A modified version of the randomized branch sampling (RBS) technique (created by Valentine et al., 1984) was utilized for the data collected from the field. This method (RBS) was used for site selection and tree selection to determine which tree would be measured for its height, diameter at breast height (DBH), average crown width, and age (determined via increment cores) (Amichev et al., 2016a).

1.4.2.2 Economic Relevance of Research

The outline of economic associations for carbon sequestering and storage techniques was established by researching similar jurisdictions concerning their carbon pricing and programs for carbon reduction. Similar jurisdictions include other provinces within Canada, the state of California, the United Kingdom, and other international governments, which are leading in carbon reduction management strategies, such as Sweden, Norway, Switzerland, and Finland.

This study was conducted through internet searches on governmental websites and private environmental programs.

1.4.2.3 Develop/outline Carbon Life Cycle Assessment

When the carbon life cycle stages of the six shelterbelt species are outlined, the relevant environmental cost can be attached to each individual life stage. With an understanding of price of a tonne of CO_2 by province and country, a monetary value could be attributed to the shelterbelt at different stages of production, transportation, use and end of life. This information can be helpful in developing potential financial rebates that could be offered by public agencies for the adoption and retention of shelterbelts in Saskatchewan.

1.5 Scholarly and Societal Relevance

1.5.1 Scholarly Relevance

This study hopefully serves as the basis for future scholarly work regarding LCAs of planted shelterbelts, carbon prices relative to agricultural management plans, and a beneficial management practice (BMP). The economic relevance (i.e., value of shelterbelts based on price of carbon) of the different life cycle stages can provide context for recommendations regarding policies. However, development of such policies is left for future research in this area.

1.5.2 Societal Relevance

The societal importance of this study is increasingly relevant due to the current state of carbon pricing at the provincial, national and global levels. To reduce GHG emissions, some policies, such as imposing a carbon tax, may be necessary. Such a measure will increase the cost of production of some goods and services and reduce the income for those who have higher carbon footprints. Discussion regarding producers and businesses who adopt management practices that lower the level of GHG emissions receiving a rebate or reduced price on their carbon tax may be made based on this study.

1.6 Limitations and Constraints

The data required to create a complete and comprehensive LCA is intensive and large scale. The input values from the production and maintenance life stage of the shelterbelt species is highly variable and may require many assumptions. The available literature cites some light on these values; however, the process of analyzing these input costs first-hand were beyond the scope of the present study. Thus, it is plausible that the existing literature may differ from the Saskatchewan context of nursery operations. Assumptions were made about certain components of the life cycle assessment due to the scope of the project.

Another limitation of developing a carbon life cycle assessment is that it cannot account for the variability in types and intensities of maintenance activities that the individual producer could adopt for the shelterbelts. The Carbon-LCA outlines different types and intensities of maintenance; however, it does not include every type of management technique, which may affect the level of carbon being stored or emitted.

1.7 Dissemination: Tool Kit

One objective of the shelterbelts project funded by the Agricultural Greenhouse Gases Program 2 (AGGP2) is to develop a Shelterbelt Decision Support System (DSS) that a producer can use for decision making regarding management practices. The DSS combines information on the most common shelterbelt designs and management activities used based on the different soil zones in Saskatchewan. The DSS also includes information on the carbon pools and fluxes between shelterbelt designs and management activities, the carbon life cycle of planted shelterbelts, existing and potential economic tools regarding adoption and removal of shelterbelts. This DSS takes a form as a free application that can be downloaded onto a computer or smartphone for easy accessibility and the ability to utilize it in the field.

The contributions of this study to the DSS include the amount of net CO_2 sequestered by the different shelterbelt species at different ages. Depending on the final format of the DSS, the results of the present study can enable the user to enter the amount (number of trees) or length (km) of shelterbelt, type of species and maintenance level in order to calculate the estimated amount of CO_2 sequestered and stored on their land by existing and proposed shelterbelts. The DSS app will be able to provide an estimate of the monetary amount attributed to CO_2 sequestered based on the present carbon emission pricing and any existing programs that may offer rewards for carbon sequestration, should they exist.

CHAPTER 2: CARBON LIFE CYCLE ASSESSMENT OF SHELTERBELTS IN SASKATCHEWAN – SEEDLING PRODUCTION AND TRANSPORTATION PHASE

2.1 Introduction

Production of shelterbelt seedlings to be planted on the farms and transportation of seedlings from the point of production to the farms are the first two phases of the Carbon Life Cycle Assessment of Shelterbelts in Saskatchewan.

2.2 Objectives of Study

The societal importance of carbon sequestration and storage is increasing in recent years in response to societal concerns over with the impacts of climate change. As carbon pricing policy begins to be enforced in Canada and globally, there is a need to understand the carbon sequestration capability of shelterbelt trees and shrubs. In order to understand the overall carbon balance of a bio-economic activity, its carbon production and sequestration for all life cycle stages need to be quantified.

The life cycle stages for a typical shelterbelt include production, transportation, use and eventual removal/disposal. The first stage of the carbon life cycle assessment for shelterbelt tree and shrub species is the production of seedlings and the shipment of these seedlings to their eventual location of planting. The objective of this chapter is to outline and estimate the quantity of CO_2 produced (emitted) during the production and transportation stages of the seedlings prior to their starting the farm-level life stages.

2.3 Methodology

2.3.1 Introduction to Methodology

The methodology utilized for this phase of activities included quantitative methods involving collection of data on the inputs required in the life cycle stages of production and transportation of seedlings. The goal, scope and function unit of the research are outlined in the following sub-sections. An in-depth explanation of the data collection and inventory analysis along with details on production of GHGs in the production of seedlings and their transportation to farm locations are described.

2.3.1.1 Goal, Scope, and Functional Unit

The goal of this study is to determine the CO_2 emitted and/or sequestered by production and transportation of shelterbelt seedlings in Saskatchewan using an LCA. The functional unit for the complete Carbon-LCA (including production, transportation, and farm-level operations) was measured as the number of seedlings that would be recommended for one km of shelterbelt. This value differs based on the type of species — coniferous, deciduous, or shrub seedlings being planted. This analysis covers the production of seedlings using a general type of production, meaning one analysis was conducted to include all types of seedling (i.e., coniferous, deciduous, and shrub), rather than conducting multiple analysis for separate types of seedling. This generalization was made as the inputs and values collected from the nursery do not specify any differences between the productions of different species of seedlings.

2.3.1.2 Systems Boundary

The systems boundary for this phase of LCA work was based on two considerations:

1. All the operations required in the tree nursery to prepare the shelterbelt seedlings for purchase/use.
2. The temporal boundaries for the shelterbelt production stage is based on one year of average production level.

2.3.1.3 Data Collection and Inventory Analysis

The data for the production of shelterbelt seedlings were sourced from a Saskatchewan tree nursery, Shand Greenhouse, which is located in Estevan, Saskatchewan. The greenhouse was built in 1991, adjacent to the SaskPower Shand Power Station (SaskPower, 2019b). These data were collected via personal communication (phone interviews and email correspondence) with the management of the SaskPower Shand Greenhouse (contact people were Bruce Hesselink, and Shelley Heidinger). The Shand Greenhouse provides shelterbelt tree seedlings for purchase by landowners in the province of Saskatchewan. It additionally provides promotional seedlings to schools, communities and individuals free of charge (SaskPower, 2019b). Shand

Greenhouse estimates that they produce approximately 500,000 plant seedlings on an annual basis (SaskPower, 2019a).

Data were also sourced from similarly scaled greenhouse operations, such as the University of Saskatchewan campus greenhouses[3], located in Saskatoon. Companies, such as Jays Transport, Beaver Plastics, and Shelterbelt Solutions, were contacted to provide information on equipment and materials used, and other required values for the analysis (e.g., hours to complete actions). Data collected for this stage of the LCA were entered into a LCA software program SimaPro, which calculated the emissions from the overall life stages of production and transportation, as well as from individual stages. Proxy substances were used when sufficient information on a specific product did not exist.

2.3.2 Methods

As noted above, the operational costs and inputs associated with the production of seedlings intended for shelterbelt establishment were based on all operations of Shand Greenhouse, but excluding heating cost. The reason for this exclusion was that the Shand Greenhouse utilizes waste heat generated from the neighboring SaskPower coal-fired power station, for which no records are kept. In order to determine this input cost, a greenhouse-heating calculator (ACF Inc., 2019) was utilized along with similar observations from other greenhouse operations (i.e., University of Saskatchewan campus greenhouses).

Within SimaPro, a number of methods are available depending on what environmental costs are to be analyzed. 'Selected LCI' results is a method within SimaPro that generates the focused values on a number of GHGs[4], including CO_2. Applying this method, the overall production of CO_2 can be determined within the entire process of production, as well as its breakdown by individual process inputs. For the purpose of this study, only CO_2 values outlined by SimaPro are reported; in other words, other environmental impacts (including other GHGs) are not included in the presentation).

[3] Personal communication with Kevin Hudson, Energy and Emissions officer at the University of Saskatchewan.

[4] Other GHGs and emissions this method displays are non-methane volatile organic compounds (NMVOC), CO_2, sulphur dioxide, nitrogen oxides, and particulates as well as land occupation, biochemical oxygen demand (BOD), and cadmium.

2.3.2.1 Assumptions:

In order to undertake the LCA, several assumptions were made. These included:

1. Inputs that were referred to as being "very few" (e.g., plastic pots) or that did not have a recordable amount specified from data sources were omitted from this study.
2. Data regarding heating requirements were sourced from a review of literature as Shand Greenhouse utilized waste heat from the neighboring SaskPower power station to heat their greenhouses.
3. As the source location of the seeds was not specified, this LCA was conducted under the assumption that the seeds were from the stockpile of seeds on site that Shand Greenhouse reported.
4. All seedlings (i.e., conifers versus deciduous) required the same inputs and processes during the production phase. This assumption was made for reasons of lack of data.

2.3.2.2 Production

The growing season for spruce and pine trees (proxies for white spruce and Scots pine) begins with seed stratification, a process where seed dormancy is fragmented in order to promote germination in the fall, seeds were sown in December and seedlings then were moved outdoors in May and harvested in October-November. Manitoba maple is sown in the spring and harvested in fall, with the majority of its growth occurring outside. Green ash seeds are stratified in March, sown in May, and moved outdoors in August, then packaged in October. Hybrid poplar is grown from hardwood cuttings collected over the winter months, then planted in May and grown for one outdoor season before harvest, which occurs in late October. Caragana is sown in May without seed stratification, moved outdoors in August and packaged in October (Hesselink, 2018).

The operational costs of the Shand Greenhouse for the production of seedlings was 61% of overall costs while administration claimed represented 39% of overall costs. The administrative costs included management salaries, benefits, corporate training, travel, contract services, office supplies, advertising, vehicles, distribution expenses, and capital depreciation (Hesselink, 2018).

2.3.2.3 Inventory

Infrastructure and Land Use: The land used for growing seedlings was reported as 0.33 hectare (Heidinger, 2018). This value was entered into SimaPro as a land use change to annual crop. The infrastructure at Shand Greenhouse consisted of a headerhouse, two outdoor shade houses, two storage buildings, a greenhouse, as well as one storage Quonset available off-site. The off-site Quonset was not included in the LCA, as data for the energy and inputs required for this infrastructure were neither available nor were the processes specific to the production of seedlings dependent on this infrastructure. The dimensions and uses of the infrastructure are reported in Table 2.1.

Table 2.1 - Inventory of Buildings at Shand Greenhouse, Estevan, SK

Buildings	**Area (m^2)**
Headerhouse	490
Outdoor shade houses (2)	2,328
Storage buildings (2)	223
Greenhouse	1,486.5

The on-site infrastructure was included in the LCA. Within SimaPro, there is an input value from the Ecoinvent database (as shown in Appendix - Table A.1) for the operation of a greenhouse of a specified area. This function allows for the percentage of environmental costs from the construction of the building including production of building materials. Since these assets have a life of more than one year, this aspect was also accounted for in the LCA. However, the input values for buildings in general were not included within the Ecoinvent database. The option of entering a building into LCA accounts for estimating environmental costs is not appropriate since the emissions created by the construction of the infrastructure are not representative for one year of use. For this reason, an annual apportionment cost of infrastructure was used to reflect one year of production, which was used in the LCA. There are concrete floors throughout the greenhouse and the headerhouse. The header house (area and offices) has metal studs with metal exterior with gyproc and insulated interior. The two storage buildings are set on pavement with concrete footing and a metal building (studs, siding and roof)

(Heidinger, 2018). The lifespan of buildings can vary based on a number of factors, such as environmental conditions, maintenance and use of the building. The life expectancy of a steel and concrete building has been reported to be 60 years (Ryan, 2014; O'Connor, 2004). Therefore, the environmental emissions for the construction of infrastructure at Shand was based on 1/60 of the total emissions (equivalent to one year of production), as recommended by the Southern Coast Air Quality Management District (SCAQMD, 2008).

Equipment and Fuel: Shand Greenhouse utilized one truck for their operations as well as for part of the seedling distribution. An estimated 600 gallons of gasoline was required for 150 hours of operation for the truck (Hesselink, 2018). In addition, a transport carrier (Jay's Transport) was used for other distribution of seedlings. A tractor is utilized for some of the operations, requiring an estimated 85 gallons of diesel fuel for 150 hours of operation (Hesselink, 2018).

Chemicals: For weed control, several types of chemicals were used for the 2018 production of seedlings. These data were provided by Bruce Hesselink, at Shand Greenhouse (Table 2.2). At the Shand Greenhouse, some weed control is done by hand; hand pulling of weeds occurs throughout all growing bays at least once soon after seeding and then again, when plants are more established and ready for packaging (Hesselink, 2018). The chemicals listed in Table 2.2 were applied according to a monitoring of the threshold levels and the pest lifecycles. In general, the chemical treatments were required for winter-grown crops (seeds sown in December/January), and early spring (May), prior to being moved to outdoor growing areas for conditioning (Hesselink, 2018).

Materials: A table of all the inputs (Table 2.3) required for a year of seedling production was created based on information provided by Shand Greenhouse managers Bruce Hesselink and Shelley Heidinger. The inputs included seeds, materials required for seed stratification and storage, planting materials (fertilizer, trays and containers), and materials for packaging (boxes and plastic wrap). The unit p denotes piece or singular unit.

Table 2.2 - List of Chemicals used for Tree Seedling Production in Shand Greenhouse 2018 Operations for 500,000 seedlings

Input	**Annual amount**	**Unit**
Avid (Insecticide)	22.5	ml
Citation (Insecticide)	300	g
Dipel (Bioinsecticide)	285	g
Dynomite (Insecticide)	72	g
Enstar (Insecticide)	6	ml
Intercept (Insecticide)	98.4	g
Maestro (Fungicide)	8170	g
Pylon (Insecticide)	450	ml
Round-Up Weather Maxx (herbicide)	6	L
Senator (Fungicide)	7400	g
Trounce (Insecticide)	4200	ml
Truban (Fungicide)	543	ml
Zerotol (Fungicide)	10.46	L

Table 2.3 - Inventory of Inputs used for Seedling Production at Shand Greenhouse for 500,000 Seedlings

Input	**Amount**	**Unit**
20-8-20 All Purpose High Nitrate fertilizer	645	kg
Sulphuric acid	1	L
Clorox Bleach	1	L
Incubators	2	p
Nylon mesh bags	50	p
Purified water	50	L
Seeds	4,203,390	P*
Spencer-Lemaire foldable Plastic Trays	2	p
Styroblock Containers	8500	p
Meat wrap plastic wrap	2.50	g
Small plastic bags	1.75	g
Large box	1	kg
Small box	400	g

* The unit ‘p’ denotes piece or single unit.

Seeds: The number of seeds used in a year of production of seedlings varies based on the number of trays, crops, seed lot, etc. Trays are used for seeding in the production of seedlings. The variation occurs between what is planned versus what is actually used. Shand Greenhouse utilizes a system of a number of cells within a tray and the number of seeds planted into a tray. The planned number is equal to the number of cells in a tray multiplied by number of seeds per cell. The amount that is actually used is measured in grams in each seed lot (approximately 3 seeds per gram). The planning includes over and under seeding, miscounts, and extra stratification for future use. As an example, for the year 2018, the planned number of seeds was 2,603,491; however the actual seed used, based on grams in each seed lot, ended up to be 4,203,390. Seeds utilized by Shand Greenhouse are mostly picked locally by Shand staff or purchased from prairie farms. Some conifer seeds were sourced from provincial forestry nurseries, mainly from those located in Ontario, Alberta and Manitoba. Many of these forestry nurseries are no longer operational; however, Shand Greenhouse has, in the past, stockpiled seeds and currently draws from this stockpile for their annual seedling production inputs.

Seeds are processed and cleaned on-site and scarification is done under controlled conditions where the surface is sterilized and/or acid scarified (Hesselink, 2018). Chemical scarification removes the surrounding structure of the seed, which is done using sulphuric acid and agitation during treatments (Rostami and Shasavar, 2009). This process involves bench-top processing equipment, precision-controlled refrigerator-incubators, nylon mesh bags, purified water (approximately 50 L), and small amounts, approximately 1 L each, of bleach or the aforementioned sulphuric acid (Hesselink, 2018). The stockpile was sourced from regional forests and tree nurseries. As the data for the sourcing of these seeds was not available, it was not included in the scope of this research.

Seedlings: Shand Greenhouse reported that the weight of seedlings after they are established and ready to be distributed to landowners can vary dramatically depending on species and moisture content. It was reported that the weight of a shrub species, (i.e., acute willow), was 95 g per seedling. The weight for a plains cottonwood (proxy for hybrid poplar), a deciduous seedling, was 64 g (Heidinger, 2018).

Planting Media: The potting mix (or planting media) utilized by Shand Greenhouse is soil-less but peat-based. This media is sourced from a Canadian sphagnum processor, Premier Tech or Sun Gro. Determining the exact amount of potting mix used on an annual basis is difficult as Shand Greenhouse over-orders the estimated amount required and then utilizes on a need basis (i.e., exact measurements are not made). Shand Greenhouse manager estimated that for the two crops (summer and fall) would require approximately 117,700 L of mixed media. They ordered 660 bales of the planting media for estimated requirement of 555 bales. Each bale is 3.8 cubic ft. and expands to roughly 212 L of mixed media. The mixed media is condensed during its packaging and expands considerably when removed (Hesselink, 2018).

Fertilizer: The fertilizer product utilized by the Shand Greenhouse was the Plant-Prod 20-8-20 — All Purpose High Nitrate (Hesselink, 2018), a high nitrate all-purpose fertilizer (Master Plant-Prod Inc., 2019). The average annual amount of fertilizer used is 645 kg (43 bags at 15 Kg per bag) and is applied frequently throughout the growing cycle. The majority of the fertilizer blend was applied through the irrigation system in conjunction with crop watering.

Plastic and Packaging: The majority of the seed stock is grown in Styroblock containers, and a small quantity in grown in Spencer-Lemaire foldable plastic sleeves/trays, both ordered from Beaver Plastics, located in Acheson, Alberta, a little over 1000 km distance to Estevan, Saskatchewan. The foldable plastic sleeves consist of corrugated flat sheets that create cells for plants to have within growth. Shand Greenhouse manager estimates 8,500 Styroblock containers and 100 trays containing 1,000 inserts, both of which have an expected life span of five years, if these were to be utilized annually. The weight of these different plastic containers is approximately 600 g. Environmental events, such as hailstorms, may damage the containers and sleeves and therefore decrease their life span (Hesselink, 2018).

A five-inch meat wrap plastic was utilized for packaging bundles of seedlings together. Both #112 and #77 plugs refer to the container size, with #112 plugs having a cavity volume of 80-93 ml with a seedling density (cavities/m^2) of 527, and #77 plugs having a cavity volume of 126-172 ml with a seedling density of 366 (British Columbia Ministry of Forests, 1998). The amount of plastic wrap required varies depending on the size of plugs, and the experience of a wrapper. On average, Shand Greenhouse currently supplies approximately 25,000 individual-packaged seedlings for promotional purposes. These small promotional plastic packages weigh

1.75 g per bag. Dependent on the species type, roughly 200 #77 seedlings or 250 #112 plug seedlings fit in a box. Large sized boxes and smaller sized boxes are utilized for packaging the bundles. The large boxes are of the size 8” x 15” x 18” and weigh 1 kg and the smaller boxes are of the size 8” x 7.5” x 18” and weigh 400 g. The smaller boxes are utilized more during the spring distribution process for smaller orders. During the fall, the pre-packaged stock, such as the singles, are stored in the larger sized boxes (Hesselink, 2018).

Energy and Heating: Electricity is required to provide power and heating to the entire infrastructure (not including the heating of the greenhouse) in the Shand Greenhouse operation. The annual total electricity utilized by Shand Greenhouse is 1,270,800 kWh (Hesselink, 2018).

It was reported that the greenhouse space is 16,000 square feet (ft^2), and that “*The main greenhouse is a three bay, gutter-connected structure with tempered glass roof and polycarbonate exterior walls”* (Hesselink, 2018). The temperature for the greenhouse is set at 25º C; however depending on the outdoor temperature, wind and other aspects, this temperature can reach 30-40º C (Heidinger, 2018). The energy requirements for heating of the Shand Greenhouse were not available; therefore, an alternative estimation of the heating requirement was made. Heating of industrial size greenhouses is commonly accomplished by electricity, coal, or natural gas. For this LCA, it was assumed that heating is done by natural gas. In order to estimate the amount of natural gas required to heat a greenhouse operation of the scale of Shand Greenhouse, data on building scale, comparative data from the literature, applied calculators (discussed below), as well as requested information from other similarly scaled greenhouse operations in Saskatchewan were obtained. The calculator provided by ACF Inc. (2019) required the area of the structure, inside temperature, average low temperature, number of heating months, and the heat loss value as parameters affecting heating costs. The Shand Greenhouse area is 1,486.5 m^2 with an internal temperature is set at 25ºC. The number of heating months is the period during the year that heating occurs. Shand Greenhouse’s growing use occurs from December – September (10 months) depending on differences in species and when the seeds are stratified and then sown (Heidinger, 2018). The average low temperature was calculated using the average low temperatures over the required heating months in Estevan, Saskatchewan (December through September). Figure 2.1 shows the average high and low temperatures for the area (Weather Atlas, 2019).

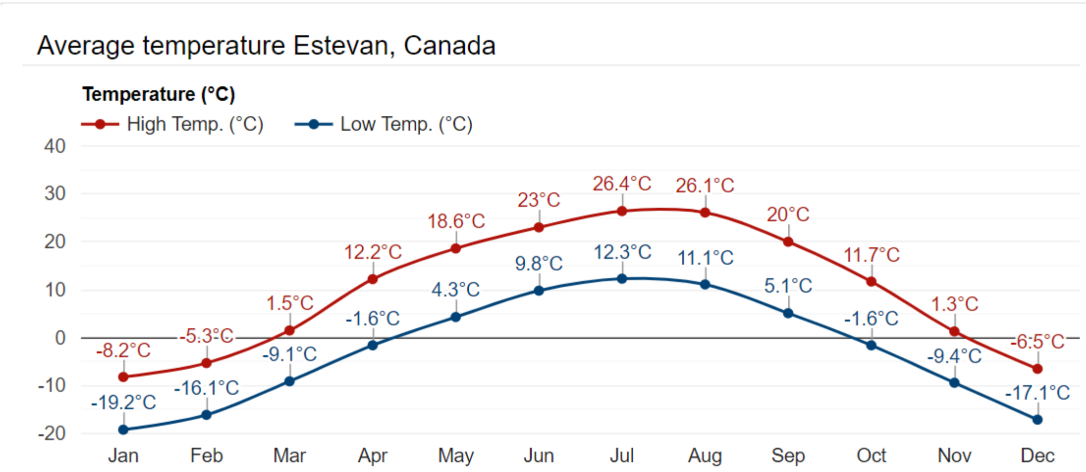


Figure 2.1- Average Temperatures in Estevan, Canada (Weather Atlas, 2019)

The heat loss (R-value) was determined on the basis of building materials and coverings of the greenhouse. The R-value is a building's capacity to resist heat loss with a higher value meaning a greater insulation. This value is dependent on the material, thickness and density of the building material. For reference, plain glass would typically have an R-value of 0.03 ft^{2}◦ Fh/BTU (British Thermal Unit) and gypsum board (drywall) and fiberglass would have R-values of 0.45 and 3.50 ft^{2}◦ Fh/BTU, respectively (Pisupati, 2018). The Shand Greenhouse has a tempered glass roof and polycarbonate exterior walls so the estimated heat loss is 0.90 ft^{2}◦ Fh/BTU (ACF Inc., 2019).

Based on the heating period and R-value estimates for Shand the total amount of natural gas required to heat the greenhouse for 10 months was calculated to be 2,843,272 ft^{3} (80,512.5 m^{3}) based on available units and use of heating requirement calculator (ACF Inc., 2019). A comparison of this value to other natural gas heated greenhouse operations in Saskatchewan was made using the natural gas usages for the greenhouses on the University of Saskatchewan. The University of Saskatchewan greenhouses, in Saskatoon, SK, were divided into two categories: Grounds Greenhouse and Agricultural Greenhouse. The natural gas usage in 2018 for the Grounds Greenhouse (of the 1,041 m^{2}) was 71,641.62 m^{3} and the usage for the Agriculture Greenhouse (of the size 3,523 m^{2}) was 397,931.52 m^{3} (Personal communication with Kevin Hudson, University of Saskatchewan). Table 2.4 shows the breakdown of the area (m^{2}), annual electricity usage (kWh), natural gas usage in 2018 (m^3), and natural gas (m^3) per m^2 usage comparing the calculated values for an operation size of Shand Greenhouse should it use natural gas with the actual values for the Agricultural Greenhouse on the university campus. The monthly data for the Agricultural Greenhouse was available, therefore it is being utilized to compare the 10-month period to that of the Shand Greenhouse scenario.

Table 2.4 - Breakdown of Different Greenhouses with Respective Electricity and Natural Gas Usages/Requirements (Hudson, 2019)

Building	**Area (m^2)**	**Annual electricity use (kWh)**	**2018 Natural gas use (m^3)**	**Natural gas (m^3)/m^2**
Agriculture Greenhouse	3,523.00	1,622,593.00	318,034.33	90.27
Shand Greenhouse	1,486.50	713,833.20	80,512.50*	54.16*

* Values are not based on records, but rather from greenhouse heating requirement calculations.

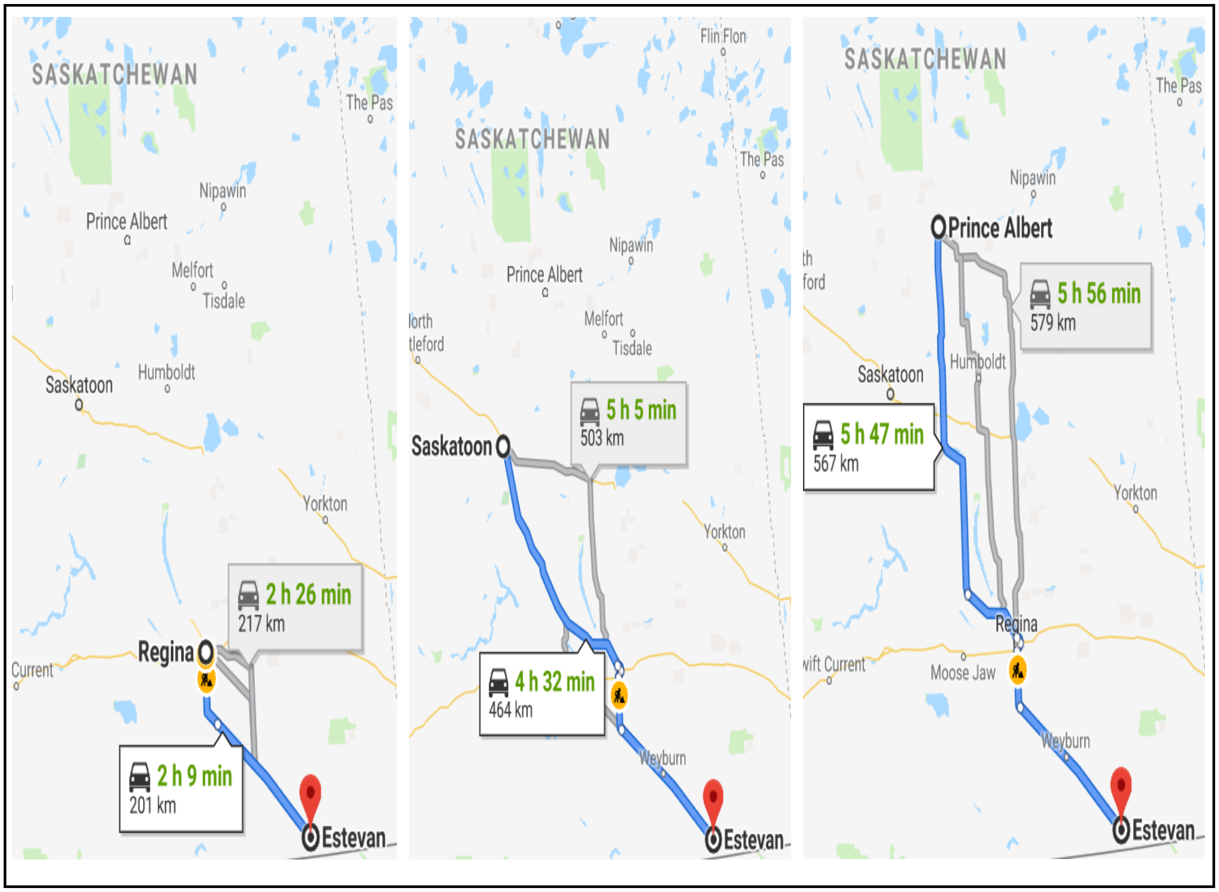
The electricity for the Shand Greenhouse was reported for the overall operations of the greenhouse, not specifically that which is directly used by the greenhouse on site. Therefore to estimate electricity required for the area of the greenhouse, an average kWh per m^2 was estimated for two greenhouses on campus (grounds greenhouse and agriculture greenhouse). The electricity utilized by the grounds greenhouse and agricultural greenhouse was reported as 499.9 kWh/m^2 and 460.6 kWh/m^2, respectively. An average of these values is 480.2 kWh/m^2, which was multiplied by the area of Shand Greenhouse to produce the estimated required energy of 713,833.3 kWh (as shown in Table 2.4). The 2018 electricity usage for the overall operation was 1,270,800 kWh (Hesselink, 2018). Electricity utilized by Shand Greenhouse was sourced from the province's electrical grid. Roughly, 84% of the electricity in Saskatchewan is generated using fossil fuels, including about 49% and 35% from coal and natural gas, respectively. Renewable energy, primarily hydroelectricity, accounts for the remaining 16% of energy production in the province (Canada Energy Regulator, 2019). Table 2.4 shows the heating requirements for a 10-month period for the University's Agricultural Greenhouse and calculations for the Shand Greenhouse. The growing period for seedlings at Shand Greenhouse occur over a 10-month period, therefore two months were omitted for requiring the same level of heating.

2.3.2.4 Transportation

Shand Greenhouse either does some deliveries utilizing their own truck (Ford 150/250) or rent / hire a transport carrier (Jay's Transport). The amount that is shipped by transport carrier to the three central hubs (Regina, Saskatoon, and Prince Albert) varies from year to year. The types of transportation supplied by Jay's Transport are tractor and trailer, with an empty weight of (32,000 lbs) or a straight truck, weighing 7,711 kg (17,000 lbs) (personal communication with Jays Managers). Shand Greenhouse noted that the average shipment load involves 600-700 boxes per year under normal demand and 1,000 boxes per year on largest demand shipping years. As mentioned previously there are two different sizes of boxes; however, in this study, for simplicity reasons, this calculation was based on the assumption that the transportation of seedlings is done using larger sized boxes. This assumption is also justified on grounds that these boxes are the ones that are more commonly used. The larger boxes weigh approximately 1 kg when full, and accommodates approximately 200 #77 plug seedlings and 250 #112 plug seedlings (specification of plug types outlined above in *Plastic and Packaging*). As the average shipment load includes 600-700 boxes, it would equate to a total seedling weight of 600-700 kg. In this analysis, the higher end of the general shipments, 700 boxes (700 kg), is used for the LCA. When entering transportation as a process in SimaPro, the unit for transportation is kg-km or tonne-km. Tonne-km is a value for transportation that is mass multiplied by the distance traveled. As noted above, larger shipments are done using a transport carrier, delivering to the three central hubs within the province: The distances from Estevan to the three delivery hubs are displayed in Figure 2.2: Estevan to Regina (a), Estevan to Saskatoon (b), and Estevan to Prince Albert (c) (Google Maps, 2019).

The distance to the closest distribution hub, Regina, SK, is approximately 200 km from Shand Greenhouse, Estevan, displayed in Figure 2.2(a) (Google Maps, 2019). Assuming that the transport carrier is leaving from Regina to retrieve the shipment at Shand Greenhouse, one return trip for one shipment is required.

Trip #1 involves the empty truck traveling the 200 km to the greenhouse, weighing 7,711 kg. Therefore, the total transportation units for trip #1 was 1,542,200 kg-km. Similarly, total transportation units for trip #2 (return trip with cargo) was 1,682,200 kg-km, and for Trip 3 (which is a combination of trip #1 and trip #2) 3,224,400 kg-km (3,224.4 t-km).



(a) *(b)* *(c)*

Figure 2.2 - Distance (km) from Estevan, SK to Regina, SK (a), Saskatoon, SK (b), and Prince Albert, SK (c)

The next distribution hub is Saskatoon, SK, which is approximately 464 km from Estevan, SK as displayed in Figure 2.2(b) (Google Maps, 2019). Again following the same assumption, as made above, that the transport carrier is leaving from Saskatoon, trip #1 includes the empty vehicle of traveling 464 km. Trip #1 has a total transportation unit of 3,577,904 kg-km. Trip #2, which involves the transportation of the seedlings shipment from Estevan to Saskatoon has a total transportation unit of 3,902,704 kg-km. The total transportation value, the combined trip #1 and #2, is 7,480,608 kg-km or 7,480.6 t-km.

The last and furthest distribution hub is Prince Albert, Saskatchewan; distance from Estevan is displayed in Figure 2.2(c). The distance in this equation is 567 km. Trip #1, from Prince Albert to Estevan with an empty truck has a transportation value of 4,372,137 kg-km. Trip

#2, from Estevan to Prince Albert with seedlings weight is 4,769,037 kg-km. The total transportation value for this shipment location is 9,141,174 kg-km or 9,141.2 t-km.

2.4 Results and Discussion

Results were estimated utilizing the LCA software program SimaPro using data for the inputs for the production and transportation stages of the Carbon-LCA of shelterbelt shrubs and trees at their seedling stage. Data regarding the CO_2 values for each input were outlined using exact matches or proxy products/processes to those reporting in the respective life cycle stages. Drawing from the Ecoinvent database and utilizing the method LCI Select within SimaPro, kilograms of CO_2 produced in total by various life cycles stages were estimated, using the inputs as reported above. *LCI Selected Results* is a method within SimaPro that outlines the sum of environmental indicators emitted to a compartment and therefore combines the emissions to different sub-compartments (Frischknecht and Jungbluth, 2007)

2.4.1 Seedling Production

The first life cycle stage of the Carbon-LCA for the shelterbelts is the production of tree and shrub seedlings. The total CO_2 produced by this life cycle stage, for the annual production of approximately 500,000 seedlings was 1,100,000 kg. Table 2.5 reports all the inputs involved in this process and their respective contribution to total CO_2 produced.

2.4.1.1 Emissions by Source

The highest CO_2 producing input in seedling was from electricity used for production of seedlings, which generated 83.42% of the total CO_2 emissions (equivalent to 914,712 kg). The second highest CO_2 producing input was heating of the greenhouse and other buildings by natural gas, estimated at 11.04% (121,000 kg CO_2). Relative contributions for those production inputs responsible for over 0.10% of CO_2 production for the seedling production are reported in Figure 2.3. The total estimated CO_2 emission produced during the seedling production phase for one order of seedlings (assuming the order is for 1,000 seedlings), was 2,200 kg CO_2.

Table 2.5 - CO_2 Emissions (as Actual Values and Proportional Percentages of all Inputs) by Inputs in Production Phase of Seedlings

Label	**Carbon dioxide (kg)**	**Carbon dioxide (%)**
Electricity	914,712	83.22
Heat (natural gas)	121,000	11.02
Infrastructure	28,600	2.61
Polystyrene	13,600	1.23
Tractor	7,590	0.69
Greenhouse	5,620	0.51
Nitrogen fertilizer	3,610	0.33
Irrigation	1,770	0.16
Gasoline	1,010	0.09
Peat	851	0.08
Fungicide	173	0.02
Diesel	138	0.01
Polypropylene	76.7	0.01
Insecticide	64.4	0.01
Glyphosate	63.2	0.01
Transport	37.3	0.003
Captan	31.2	0.002
Packaging film	30.3	0.0028
Acetic acid	20.9	0.0019
Land use change, annual crop	10.9	1.00E-03
Nylon 6-6	3.32	3.00E-04
Sodium hypochlorite	2.63	2.00E-04
Purified water	2.18	2.00E-04
Sulphuric acid	0.139	1.26E-05
Total	1,100,000	100.00

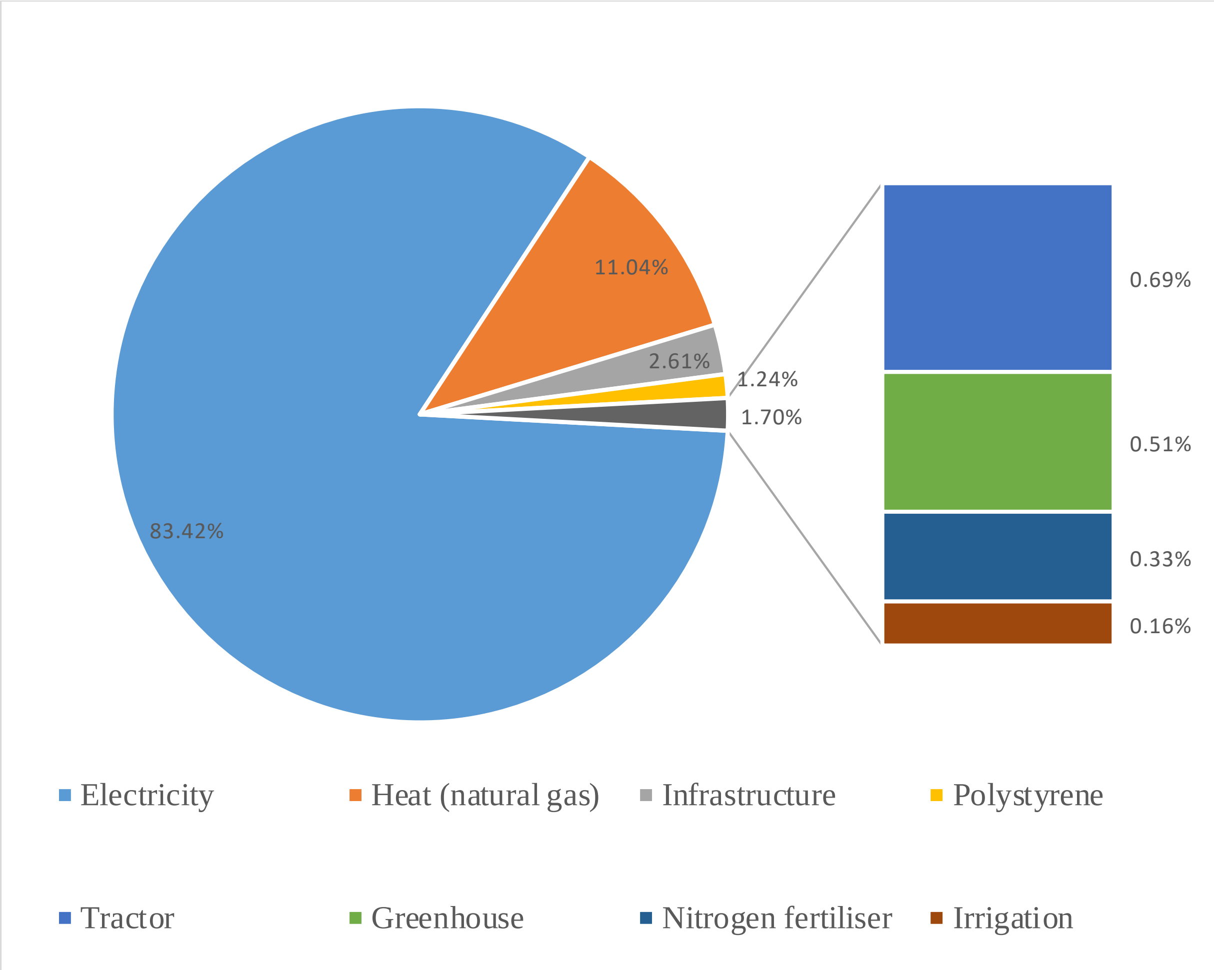


Figure 2.3 - Percentages of CO_2 Emissions for Seedling Production Inputs

2.4.1.2 Uncertainty Analysis of Production Life Stage

An uncertainty analysis was conducted utilizing the Monte Carlo simulation within the SimaPro software to determine uncertainty and risk in the results (Figure 2.4 and Table 2.6). The uncertainty values were calculated using parameters on the reliability, completeness, geographical correlation, temporal correlation, and technological correlation of each input value entered for the production phase. These parameters were utilized to account for reliability of the information, whether or not the dataset is complete, if the data is geographical correct, accuracy on the scale of time, and the accuracy of the processes and/or methods of the input data. This sensitivity analysis is important to determine the accuracy and potential variability in the values of CO_2 production for this life cycle stage of total annual production at Shand Greenhouse.

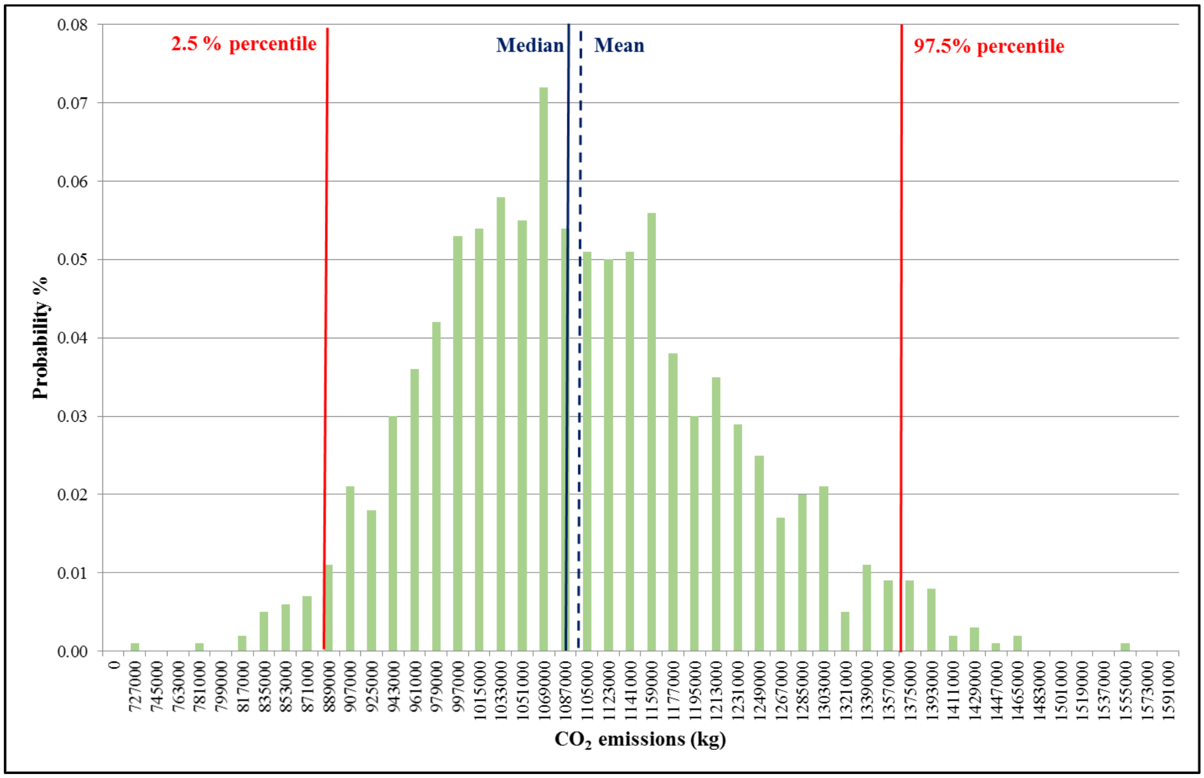


Figure 2.4 - Monte Carlo Uncertainty Analysis for the Total CO_2 Emissions for Production of 500,000 Seedlings with 95% Confidence Interval

Table 2.6 reports the mean, median, standard deviation, coefficient of variation, the 2.5% and 97.5% percentiles and standard of error mean for the value representing the CO_2 emissions associated with the production of seedlings. Figure 2.4 displays the high-low uncertainty range of the CO_2 emissions at the 95% confidence interval. As reported in Table 2.6, the mean and median for the CO_2 produced by the production of seedlings is equal to 1,100,000 and 1,090,000 kg, respectively, and are shown as the dashed blue vertical line and solid blue vertical line in Figure 2.4. The two red vertical lines denote the borders for the 95% confidence interval, where the 2.5% percentile is at 889,000 kg CO_2 and the 97.5% percentile is at 1,370,000 kg CO_2. Based on the uncertainty values on reliability, completeness, geographical correlation, temporal correlation, and technological correlation of each input found at the LCA stage, a probability of a value for the CO_2 emissions was outputted using the Monte Carlo function, as shown in Table 2.6 and Figure 2.4. These variables that impact the probability are built into the SimaPro software. The probability of the mean, the predicted value for 1,100,000 kg CO_2 emissions produced by SimaPro is slightly above 5%, and falls near the median of the bell curve. The highest probability, slightly above 7%, for a CO_2 emission was 1,090,000 kg. Figure 2.4 shows that there is 95% chance that the actual value for CO_2 emissions from the production of seedlings will fall within the range of 889,000 to 1,370,000 kg.

Table 2.6 - Monte Carlo Uncertainty Analysis Results for the Total CO_2 Emissions for Production of 500,000 Seedlings

Category	Carbon dioxide (kg)
Mean	1,100,000
Median	1,090,000
Standard Deviation	132,000
Coefficient of variation (%)	1.11
2.5%	889,000
97.5%	1,370,000
Standard error of the mean	3,880

2.4.2 Transportation

2.4.2.1 Estimation of Transportation Needs

The first step for estimation of transportation cost was to calculate the number of seedlings on a shipment required for one km of shelterbelt for the three tree categories (shrub, deciduous, and coniferous). As mentioned in the previous section , the total transportation required for the Regina Hub distribution was 3,224,400 kg-km (3,224.4 t-km), and the total transportation required for the Saskatoon and Prince Albert distribution hubs were 7,480,608 kg-km (7,480.6 t-km) and 9,141,174 kg-km (9,141.2 t-km), respectively. The same number of seedlings, and therefore weight of cargo, was assumed the same for each trip destination. The total estimated carbon dioxide emissions produced by these shipments are presented in Figure 2.5.

The above analysis provides emissions for total shipments to the transportation hub. For the purpose of this study, the analysis attributed emissions at the individual landowner level. However, a landowner ordering trees to plant a shelterbelt does not be attributed the entire carbon footprint of one shipment, as the shipment would be strategically planned to deliver to multiple buyers for one shipment. In order to estimate the CO_2 emissions created in an LCA for one farm scenario, the percentage of the overall CO_2 that contributes to one farm scenario is required. To complete this it was assumed that 200-250 seedlings are in a box and a shipment can hold 700 boxes, the total number of seedlings expected in a shipment via transport carrier would be 140,000 to 175,000 seedlings. For this study, an average value of 157,000 seedlings was used. If a landowner were ordering 1000 seedlings, the farm scale proportion of the transportation burden would be as shown in Equation (2.1):

$$\textit{Proportion of transportation burden} = \frac{1000}{157{,}000} = 0.006\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

Therefore the CO_2 production attributable to one landowner to plant one km of caragana shelterbelt, or 1,000 trees, is 0.006% of the overall CO_2 production from the transportation. For example, a scenario transporting 1,000 tree seedlings to Regina represents emissions of 0.006% x 6,080 kg CO_2 = 36.48 kg CO_2 (as shown in Table 2.7).

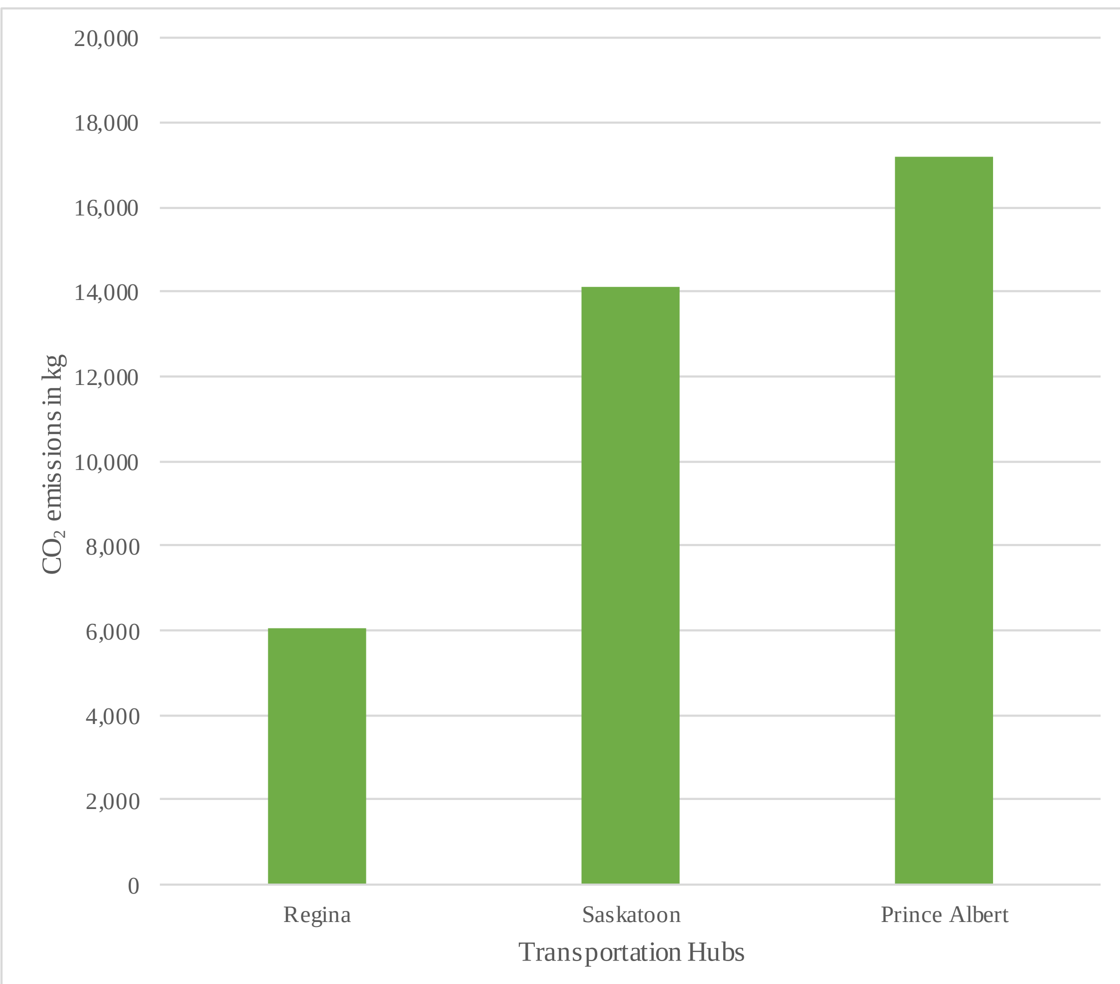


Figure 2.5 - Total CO_2 (kg) Emissions by Transportation Hubs for Full Shipment (157,000 seedlings

Table 2.7 - Total CO_2 (kg) per Shipment and per Order of 277 (coniferous), 400 (deciduous) and 1000 (shrub) Seedlings

Delivery hub pickup (Roundtrip)	Full shipment (157,000 seedlings)	Shipment of 277 seedlings	Shipment of 400 seedlings	Shipment of 1000 seedlings
Regina	6,080	12.18	18.24	36.48
Saskatoon	14,100	28.20	42.30	84.60
Prince Albert	17,200	34.40	51.60	103.20

To completely capture the emissions attributable to seedling transportation the CO_2 produced by the shorter trip from delivery hub to farm needs to be accounted for. This estimation was based on an assumption of a light load transportation location is 50 km away from the delivery hub. By creating a base value for 50 km as an addition to the larger deliveries done by Shand Greenhouse via Jays Transport, a farm or land that is 50 km or any increment of 50 km away from a delivery hub can be accounted for in specific LCAs. The transport value, expressed as kg-km, of this portion of the transportation is shown in Equation (2.2):

$$kg - km = \; distance\, from\, hub\, to\, farm\; (km) x\; the\; weight\; truck\; with\; a\; load\; of\; seedlings\; (kg) \ldots\ldots \quad (2.2)$$

The distance between a farm and the delivery hub was assumed to be 50 km and the empty weight of a class 2a smaller size standard pickup truck is roughly 2,041 kg (Office of Energy & Renewable Energy, 2010). However, the number of seedlings ordered and therefore weight of seedlings varies and is dependent on the species, length and number of rows a landowner wants to plant. In this study, utilizing the functional unit scenario of a one row kilometre long shelterbelt as a base order, the number of seedlings varied from 277 (coniferous) to 1,000 (shrubs). Using information gathered from the Shand Greenhouse, 200 to 250 seedlings can fit in a box, and a full box of seedlings weighs roughly 1 kg. In order to fill an order of 1,000 trees (assuming a larger order is more commonly placed), 4 to 5 boxes of seedlings is required, equating 4-5 kg. For the LCA, the higher weight of 5 kg was used.

Therefore, the relationship for this transportation phase becomes as shown in Equation (2.3):

$$Kilogram\ kilometre\ value\ of\ transportation:\ 50\ km\ x\ (2{,}041\ kg + 5\ kg)$$

$$= 102{,}300 kg - km \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.3)$$

The fuel consumption required for this trip would be roughly 2 gallons of gasoline to travel 50 km (Office of Energy Efficiency and Renewable Energy, 2012). The CO_2 emission for the additional travel of 50 km from a distribution hub is 41.9 kg.

2.4.2.2 Uncertainty Analysis of Transportation Stage

To understand the distribution of transportation costs an uncertainty distribution for the transportation from Shand Greenhouse (Estevan, SK) to the Saskatoon, SK hub was developed (Figure 2.6 and Table 2.8).

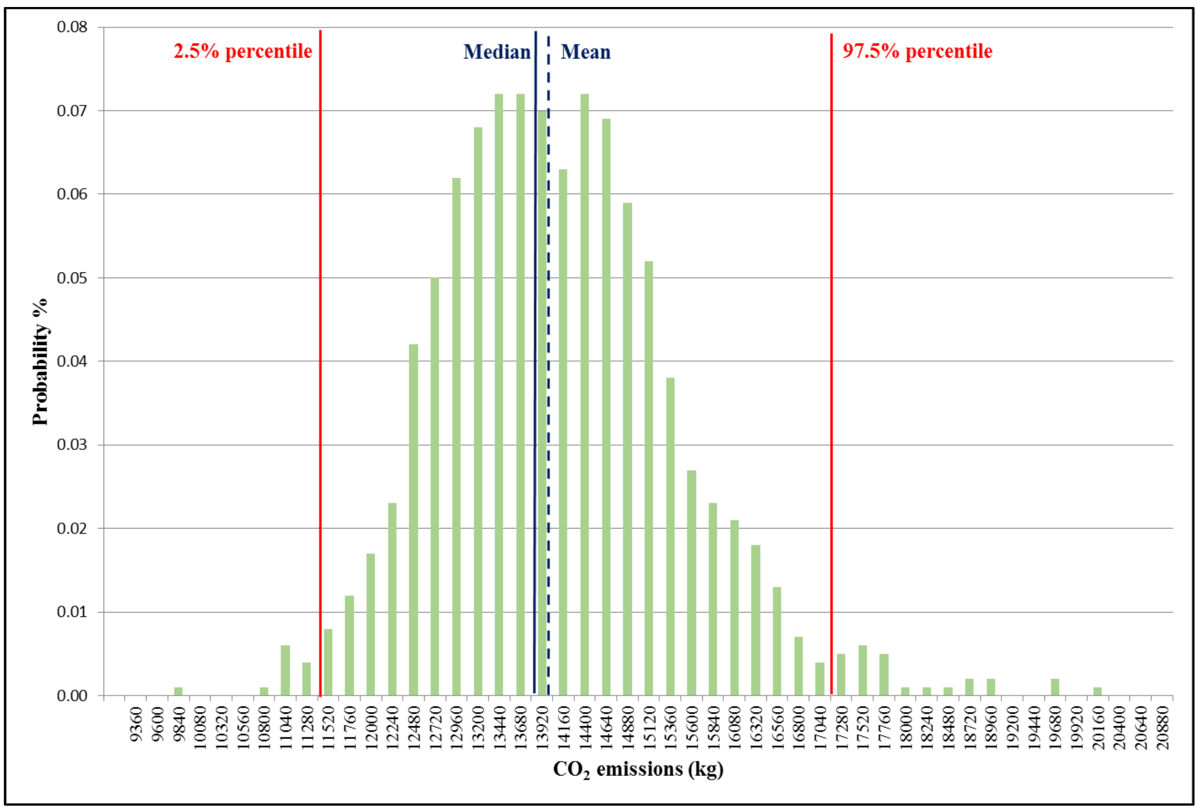


Figure 2.6 - Monte Carlo Uncertainty Analysis for Total CO_2 Emissions for the Transportation of Seedlings to Saskatoon, SK with 95% Confidence Interval

The mean and median for the CO_2 produced by the production of seedlings were equal to 14,100 and 14,000 kg, respectively, and are shown as the dashed blue vertical line and solid blue vertical line, respectively, in Figure 2.6. The two red vertical lines denote the borders for the 95% confidence interval, where the 2.5% percentile is at 11,700 kg CO_2 and the 97.5% percentile is at 17,200 kg CO_2.

Table 2.8 - Monte Carlo Uncertainty Analysis for the Transportation of Seedlings to Saskatoon, SK with 95% Confidence Interval

Category	Carbon dioxide (kg)
Mean	14,100
Median	14,000
Standard Deviation	1,360
Coefficient of variation (%)	9.61
2.5%	11,700
97.5%	17,200
Standard error of the mean	42.90

Based on the uncertainty values on reliability, completeness, geographical correlation, temporal correlation, and technological correlation of each input found at the LCA stage, a probability of a value for the CO_2 emissions was estimated using the Monte Carlo function built within the SimaPro software. As shown in Table 2.8 and Figure 2.6, the probability of the mean, the predicted value for 14,100 kg CO_2 emissions produced by SimaPro is 7%, and falls near the median of the bell curve. The highest probabilities, which fall slightly above 7%, are CO_2 emissions of 13,440 kg, 13,680 kg and 14,400 kg. Figure 2.6 shows that there is 95% chance that the actual value for CO_2 emissions from the production of seedlings will fall within the range of 11,700 to 17,200 kg.

2.4.3 CO_2 Emissions for Production and Transportation Phases

The net CO_2 emissions attributable to the establishment of a shelterbelt prior to planting the shelterbelt trees for an order of 277 seedlings, transported to Regina, Saskatoon, and Prince Albert is 0.62 tonne, 0.64 tonne, and 0.64 tonne, respectively. For a scenario of 400 seedlings, the CO_2 emissions for Regina, Saskatoon, and Prince Albert is 0.908 tonne, 0.92 tonne, and 0.93 tonne, respectively. For a scenario of 1000 seedlings, the CO_2 emitted for Regina, Saskatoon, and Prince Albert is 2.24 tonne, 2.29 tonne, and 2.30 tonne, respectively. The emissions for each shipment, i.e., 157,000 seedlings, is outlined in the fourth column of Table 2.9, with the full production value, i.e., 500,000 of seedlings produced. This column is included to show the fraction that the other values exist within from their total values.

Table 2.9 - Breakdown of CO_2 in Tonnes Emissions for each Life Cycle Stage for 277, 400, 1000 Seedlings and Total

Life Phase	**CO_2 Emissions (t) emissions for 277 seedlings**	**CO_2 Emissions (t) emissions for 400 seedlings**	**CO_2 Emissions (t) emissions for 1000 seedlings**	**Total CO_2 Emissions (t) emissions**
Production	0.601	0.88	2.20	1,100
Transportation (Regina)	0.01	0.02	0.04	6.08
Transportation (Saskatoon)	0.03	0.04	0.08	14.10
Transportation (Prince Albert)	0.03	0.05	0.10	17.20

2.5 Discussion

Based on the LCA analysis presented in this chapter, if 500,000 seedling suitable for shelterbelts are produced in Saskatchewan, total CO_2 emissions from their production would be 1,100 tonnes. These seedlings included different trees and shrubs categories. The production life stage value was assumed to be the same across deciduous, coniferous, and shrub seedling production. The highest emission producing activity was estimated to be the electricity required for the overall greenhouse operations. Based on the operations at Shand Greenhouse, about 83.4% of these emissions would be contributed by electricity use. The second highest CO_2 emission source was heating using natural gas, whose share of the total was estimated at 11%. This is comparable to the share of energy as being the highest CO_2 producing sector. In Canada, over 81% of GHG emissions are through energy use (including heating), extreme climates, varied landscapes, and dispersed communities (Natural Resources Canada, 2019).

To provide some sense of relative scale of shelterbelt production emissions, the CO_2eq emissions produced at the Saskatchewan level was 76.3 mega-tonnes (MT) in 2016 (Canada Energy Regulator, 2019). The annual production of seedlings only accounts for 0.001% of the province's CO_2 emissions. Therefore, the production of shelterbelt seedlings is a relatively minor portion of the province's emissions, and even smaller yet when an order of seedlings for shelterbelt establishment is considered.

The transportation of a full shipment shelterbelt seedling, assuming that there was 157,000 seedlings in a shipment to Saskatoon, generated a total of 14,100 kg of CO_2 emissions. Although this value does increase as shipments are made to destinations that are more northern, it does not change drastically between transportation hubs as the difference in distance is not significant. Taking into consideration, only the first two life cycle stages of production and transportation, their production stage would contribute anywhere from 95.5% to 98% of total CO_2 emissions from production and transportation stages, depending on where the seedlings are being delivered to. At this stage, transportation of seedlings makes up a very small portion of the total GHG emissions as compared to the production stage, and thus the total cost of environmental damage (contribution to climate change). However, this estimate does not include the second life cycle stages of planting (including preparing to plant), maintenance and eventual removal of shelterbelts, which is covered in detail in Chapter 3.

2.5.1 Recommendations from LCA analysis

2.5.1.1 Reducing CO_2 Emissions in Seedling Production

By highlighting the highest CO_2 producing activities associated with the production of any good or service, suggestions of areas that may require improvements to reduce emissions may be made. As electricity and heating made up the bulk of emissions for the production of seedlings, the sourcing of energy and/or heating usage have a large impact on the level of emissions created. Although reducing electricity and heating usage is one approach to reduce the GHG emissions, these services will still be required, especially considering the harsh winter climates of the prairies. Regarding the source of electricity (and heat) generation, certain methods of energy production emit higher amounts of GHGs than others. For example, in Canada, coal electricity generation accounted for 77% of the electricity-related GHG emissions in 2017, despite only accounting for 9% of the total electricity production. The use of renewable energy to fuel these processes can be helpful to decrease emissions. For Canada as a whole, hydroelectric generation is responsible for 60% of electricity production; however, in Saskatchewan, 84% of electricity is produced from fossil fuels, namely coal (49%). While natural gas accounts for 35% of the electricity in the province, and 16% is produced from renewables, specifically hydroelectricity. Additionally, Saskatchewan's per capita emissions are the highest in the country with 66.9 tonnes of CO_2eq, whereas the national average is 19.4 tonnes per capita (Canada Energy Regulator, 2019).

2.5.1.2 Reducing CO_2 Emissions in Transportation of Seedlings

The breakdown of inputs for transportation of the seedlings was the t-km of a commercial freight vehicle to travel a specified distance with a specified weight, and then the fuel required to accomplish this trip. Transportation accounts for 14% of GHG emissions in Saskatchewan (Environment and Climate Change Canada, 2018). The Clean Energy Canada (2016) working group suggests implementing a transition to zero and/or lower-emission modes of transportation as well as increasing the prevalence of clean, renewable fuel sources. Specific suggestions include the implementation of more electric vehicle (EV) charging stations and the completion of an EV highway, as well as incentives for the adoption of biodiesel as a main fuel used during a period of transition from fossil fuels to renewable fuels (Clean Energy Canada, 2016).

2.5.2 Limitations

Research on the amount of carbon that shelterbelt trees and shrubs sequester has been explored; however, the amount of carbon produced in the process of growing these seedlings to be planted in fields and around housing requires further investigation.

As is common with conducting LCAs, the nature of assumptions made is a limitation for accuracy in results. Due to difficulty in acquiring some data, and the possibility for variation in data, assumptions are often made and proxy data are often used. LCA is still a useful tool for understanding the bigger picture of a product or service and its environmental impact on the world; however, results are highly dependent on quality of data used that can vary drastically depending on a number of factors. These factors can include the lack of available data on certain input values and the requirement to compare scenarios with similar ones and perform calculations so that the closest estimation to an input value can be determined. The calculations and comparisons to create a scenario where the production of seedlings utilizes natural gas for heating rather than waste heat as reported in Shand Greenhouse's operations is an example of this. The difficulty of determining the boundaries can cause changes to the data as well. The variability that occurs between different tree nurseries and transportation methods can additionally have an impact on the amount of CO_2 that is produced in these two life cycle stages.

2.6 Conclusion

Production and transportation of seedlings to be planted as shelterbelts on farms produces CO_2 emission between 0.603 to 2.28 tonnes, depending on the type of species and distance that the seedlings need to be shipped from the southern location (Estevan, SK). A general value for shelterbelt seedling production was applied to all varieties, although in reality, some seedling varieties may differ slightly in their required inputs and growing time, which may impact their carbon emissions, but only by a very miniscule amount. The CO_2 emissions to produce a single seedling (of any species) at Shand Greenhouse is roughly 0.002 tonnes. Therefore to produce enough coniferous seedlings for a kilometre long shelterbelt composed of only coniferous trees and based on recommended spacing by the AAFC (2010) (roughly 277 seedlings), the amount of GHG emitted would equate 0.609 t CO_2. The emissions of GHG for a deciduous shelterbelt of seedlings based on the same recommendations (roughly 400 seedlings) would create 0.880 t CO_2. Finally if a full kilometre shelterbelt of shrub species were to be planted (requiring roughly 1,000 seedlings), the emissions for producing said seedlings is 2.20 t CO_2.

Regarding the transportation of seedlings, the CO_2 emissions to transport 277 seedlings to Saskatoon, SK would equate roughly 0.028 t. A shipment of 400 or 1,000 seedlings, these values becomes 0.042 and 0.085 t CO_2, respectively. These values are based on the percent of the overall shipment of 157,000 seedlings that are typical of Shand Greenhouse's seedling shipments via transport carrier. Of these total emissions, the highest emission-producing source is the electricity use by the greenhouse, estimated at 84% of the total. The second highest emitting source was the heating of the greenhouses and other buildings using natural gas, at 11%. In the scenario of Shand Greenhouse, this value is not representative of their heating requirements and emissions as they utilize waste heat, which would reduce their actual heating related emissions.

There are a number of potential suggestions to reduce emissions within these higher emissions emitting facet that can be achieved at the provincial and Canadian level. The emissions produced at the farm level of shelterbelt trees is covered in detail in Chapter 3, where the planting and planting, maintenance, and removal stages of life are outlined. The amount of CO_2 that is sequestered by shelterbelt trees and shrubs is also included in the LCA to determine the net CO_2 value over the life of the shelterbelt.

CHAPTER 3: CARBON LIFE CYCLE ASSESSMENT OF SHELTERBELTS IN SASKATCHEWAN –FARM-LEVEL OPERATIONS

3.1 Introduction

The study on the complete carbon life cycle assessment for planted shelterbelts in Saskatchewan was divided into two phases: (1) Production of shelterbelt seedlings to be planted on the farms and transportation of seedlings from the point of production to the farms; and (2) all farm-level operation of shelterbelts (planting, maintenance, life-in-field, and removal). This Chapter focuses on the last three phases of these activities.

3.2 Objective of the Study

The objective of this study is to outline the Planting, Maintenance, Life-in-field and Removal phases of the complete Carbon-LCA of shelterbelt trees and shrubs. This is the second stage to the overall Carbon-LCA of shelterbelts. The goal of this study is to determine the carbon produced and sequestered, or net carbon emissions, during the phases following the production and transportation stage of the shelterbelt seedlings. The farm level includes preparing the land for planting, maintenance, and removal of the shelterbelt. This stage of the LCA also includes the carbon sequestered throughout the trees' life in the field.

3.3 Methodology

3.3.1 Goal, Scope, and Functional Unit

The goal of this study is to determine the net carbon stored by shelterbelt trees and shrubs by analyzing the different life cycle stages. The functional unit in this study is per one km (1,000 m) of linear field shelterbelt since many of the inputs are based on an area rather than a distance. This value is based on the assumption of a length of one kilometre and the width of 1 m, required width for planting, maintenance and removal stages.

3.3.1.1 Systems Boundary

This part of the LCA includes the following components:

1. All the operations related to shelterbelts that occur at farm-level.
2. The inputs and equipment used for preparing to plant, planting, maintenance, and removal of shelterbelts were included in this study; however the raw materials and sourcing of said materials (e.g., production and transportation of chemicals used on farm) is not included in the study, due to a lack of access of inventory information.
3. The temporal boundary for the shelterbelt life cycle could be 60 to 100 years, dependent on species. Data utilized in this study from study by Amichev et al. (2016) measured shelterbelts aged 5-100. From this study, the life span of white spruce shelterbelts varied from 6-76 years, hybrid poplars from 13-55 years, Manitoba maple from 5-100 years, green ash from 5-80 years, Scots pine from 8-60 years, and caragana from 6-80 years (Amichev et al., 2016). In this study, LCA scenarios for shelterbelts at different ages (10, 20, 30, years etc.) were analyzed. The carbon sequestration of a km of each shelterbelt species is reported from age one to age 60 years on account of such information being available. Furthermore, there is no reliable reports of the carbon stocks following the age of 60 years that could have been used for this study.
4. The cultural practices associated with preparing, planting, and maintenance were outlined using recommendations by relevant literature. In this study, the stages of planting, maintenance and removal was analyzed through SimaPro to determine CO_2 production. The six species within three soil zones (Brown, Dark Brown, and Black) of the same mortality rate were also analyzed to determine the difference in carbon sequestration by region and species.
5. Data collected for this stage of the LCA were entered into a LCA software program SimaPro to calculate the overall environmental loads associated with the production of shelterbelt seedlings. Proxy substances were used when sufficient information on a specific product did not exist.

3.3.1.2 Assumptions

1. Rather than creating scenarios for every different combination of herbicide, fertilizer, irrigation and tillage use, two distinct categories of shelterbelt maintenance (ranked from low to high) were utilized.
2. Only the most commonly used chemical(s) and practice(s) in the preparing/planting and maintenance stages of the LCA were used in this study. The less commonly used options were excluded.
3. An assumption for the application rate for the herbicide, fertilizer, irrigation and tillage (HFIT) inputs during the initial years of maintenance was based on recommendations found in literature (AAFC, 2010; Government of Alberta, 2007; and The Morton Arboretum, 2019) and survey responses. Recommended irrigation application was assumed to be over the first five years of establishment, as well as the herbicide application. The practice of tillage was assumed as a one-time process during the initial year of planting, as well as the fertilizer application.
4. All carbon values were expressed as carbon dioxide (CO_2) for simplicity in understanding the values. Carbon is stored in biomass and soil as carbon; however, the values of stored and sequestered carbon were expressed it in CO_2 in this study.

3.3.1.3 Data Collection and Inventory Analysis

Relevant literature was utilized to address certain data gaps, including recommended applications of herbicide, fertilizer and irrigation.

3.3.2 Farm-Level Operations

3.3.2.1 Preparation and Planting

Preparation for planting included tilling the land and planting the trees. A base input scenario for tilling the land for the three different tree variety categories: shrub, coniferous, and deciduous, was created. For reference, caragana is a shrub species, hybrid poplar, Manitoba maple, and green ash are deciduous species, and white spruce and scots pine are coniferous species. The base scenario involved tilling the area of the functional unit; however, the action of planting tree seedlings differed by species type. The length is the functional unit of one km (1,000 m) and the width of 1 metre representing an area of tillage of 1,000 m^2 or 0.001 km^2. Assuming the use of a rotary cultivator or similar machinery, the construction of the equipment, diesel use and storage of equipment is included in the LCA, via a process function of tilling agricultural land in Ecoinvent and Agri-footprint databases. The process was entered by the area to be tilled.

The number of trees that can be planted in a kilometre stretch of land differed based on tree species and their recommended spacing. The recommended minimal spacing for shrubs is 1 metre, and minimum spacing for deciduous and coniferous trees is 2.5 m and 3.6 m, respectively (AAFC, 2010). Based on these recommended spacing the number of trees planted in a km of land are as follows: 1,000 shrubs, 400 deciduous trees, and ~277 coniferous trees.

3.3.2.2 Maintenance

Shelterbelt maintenance included application of herbicides, fertilizers, irrigation and whether or not the land was tilled (HIFT) prior to planting and any weed management surrounding the belt. There is a base maintenance level possible for the Carbon-LCA.

Herbicide: The most common herbicide used by Saskatchewan landowners in the 2017/2018 field season survey was either Glyphosate or RoundUp[5] (Appendix – Table A2). However, since little details were provided on the amount of chemical applied, the exact amount utilized in this study were based on the AAFC (2010) recommendation of application of 2.0-2.8 L of a liquid formula of glyphosate (e.g., Credit, Renegade, Roundup Original, Vantage, Victor) per acre of trees for perennial weed control. These values were then converted to the functional unit used in this LCA of 1000 m^2 (0.001 km^2), or 0.694 L of glyphosate as follows:

$$1000\ m^2 = 2.47105\ acres \qquad (3.1)$$

Then:

Calculation of required herbicide application for functional unit

$$0.247 \times 2.8\ L = 0.694\ L/1000m^2 \qquad (3.2)$$

Assuming herbicide applications occur over the first five years, the total amount of glyphosate applied would be 3.47 L per 1,000 m^2. The recommended amount of water for glyphosate dilution and application is 20-40 L per acre (AAFC, 2010). Therefore, for a 1000 m^2 of trees, the water required would be 40L x 0.247 = 9.88 L for one application and 49.4 L for five annual applications.

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[5] Glyphosate is the primary active ingredient in Roundup.

Fertilizer: The quantity and type of fertilizer applied is dependent on the current state of the soil. In soils with low nutrient levels, fertilizer applications prior to planting may aid in the establishment of the shelterbelt. In order to establish what is appropriate, it is recommended (Government of Alberta, 2007) to conduct a soil test to determine the current nitrogen, phosphorus, potassium ratio. The preferred N-P-K ratio is 75-75-150 (Government of Alberta, 2007). Based on recommendations by the Morton Arboretum (2019) on an N fertilizer application, roughly 3 lbs. (1.36 kg) would be applied per 1000 ft^2 (92.903 m^2) or 15 kg per 1000 m^2 (0.001 km^2). This is applied once during prior to planting.

Irrigation: A general recommendation by the AAFC (2010) for irrigation is one inch of water per week following planting and during the establishment period of the shelterbelt seedlings. This period of establishment is the first three to five years following planting (AAFC, 2010). The amount of irrigation required can vary dramatically depending on precipitation, which varies by the region and year. However, in this LCA, a scenario of no to low rainfall occurring was assumed. This necessitated irrigation being required as a part of a high maintenance level. One inch of irrigation per acre equates to 27,154 US gallons (USGS, 1988). If it is a particularly dry year, irrigation might be required consistently. If a landowner irrigates their shelterbelt from May through August (16 weeks), the amount of water needed was based on the area that requires irrigation, which for this scenario is 1,000 m^2 (0.001 km^2). Therefore, one inch of irrigation for 1000 m^2 represents 6,707 US gallons a week for 16 weeks as shown below:

Calculation of one inch of water daily over an area of 1000 m^2 over 16 weeks:

$$27{,}154\ US\ gallons\ x\ 0.247 = 6{,}707\ US\ gallons/1000\ m2 \qquad (3.3)$$

This equates to 1,218,660 L of water over 3 years.

Tillage: A common response from the survey regarding the preparation prior to planting that occurs as well as once or twice during initial years was the process of tilling the intended area that the shelterbelt was to be planted. This process is the same as that covered in the tillage for preparation of planting above (see 3.3.2.1 Preparation and Planting). In this study, it was assumed that tillage occurs over an area of 1000 m^2 as a one-time process during the initial year of shelterbelt establishment as a form of weed control. Assuming the use of a rotary cultivator or similar machinery, the construction of the equipment, diesel use and storage of equipment is included in the LCA, via a process function of tilling agricultural land in Ecoinvent database.

3.3.3 Life in Field - Carbon Sequestration and Stocks

Data representing carbon stock value estimates of the six shelterbelt species (caragana, green ash, hybrid poplar, Manitoba maple, scots pine, and white spruce) were made by Amichev et al. (2016). This was based on destructive sampling whereby 50 trees and shrub species were harvested overall, 10 of which were green ash, 9 hybrid poplar, 12 caragana, 9 Manitoba maple, 3 scot pine, and 7 white spruce (Amichev et al., 2017). Additionally, data regarding destructive sampling were used from Kort and Turnock (1999). The tree state for this sampling involved live, and leaf-on trees biomass. The shelterbelt ages included 5 to 100 year old trees. The sampling utilized whole tree weight, RBS (randomized branch sampling) method, tree cookie and branch samples and included different soil depths and root and liter layer samples. An assumption of a 50% carbon content of wood was made, based on the CBM-CFS3 carbon model (Amichev et al., 2017). As noted earlier, the data collected for the carbon stocks of the six shelterbelt tree and shrub species was recorded only until age 60 of the trees, since there is no reliable data on carbon sequestration rates following age 60. Carbon sequestration and saturation of the trees is dependent on a number of factors, including average life span of the tree. The lifespan of hybrid poplar is 30 to 50 years and the lifespan of caragana, green ash, and Manitoba maple, Scots pine, and white spruce is 50+ years (AAFC, 2018).

3.3.3.1 Soil Clusters

In the overall project, 31 soil clusters were created by grouping 106 agricultural ecodistricts within the province. (Amichev et al., 2012). Figure 3.1 displays the 31 soil zone clusters. The amount of C sequestered by the shelterbelt trees is measured by a number of variables. These included: six species, past (1950s to 2015) and present (2016 to 2075) climate ranges, four mortality rates, two C data types including C stocks (Mg C km^{-1}) and C rates measured in terms of Mg C km^{-1} yr^{-1}, three shelterbelt components including Total Ecosystem Carbon (TEC) Biomass C, Dead organic matter C, and 31 soil clusters. Rather than estimating 8,928 scenarios including every different combination of specific variables were selected. For this study, data based on past carbon budget model (CBM) values and total ecosystem carbon (TEC) were utilized for representative clusters in the Brown (BRN), Dark Brown (DBRN_2), and Black (BLK) soil zones. The reasoning behind the selection of representative clusters in each of the soil zones was based on which clusters had the highest cumulative shelterbelt carbon stocks from the most recent shelterbelt inventory. These clusters were identified as BRN for the Brown soil zone, DBRN_2 for the Dark Brown soil zone, and BLK for the Black soil zone.

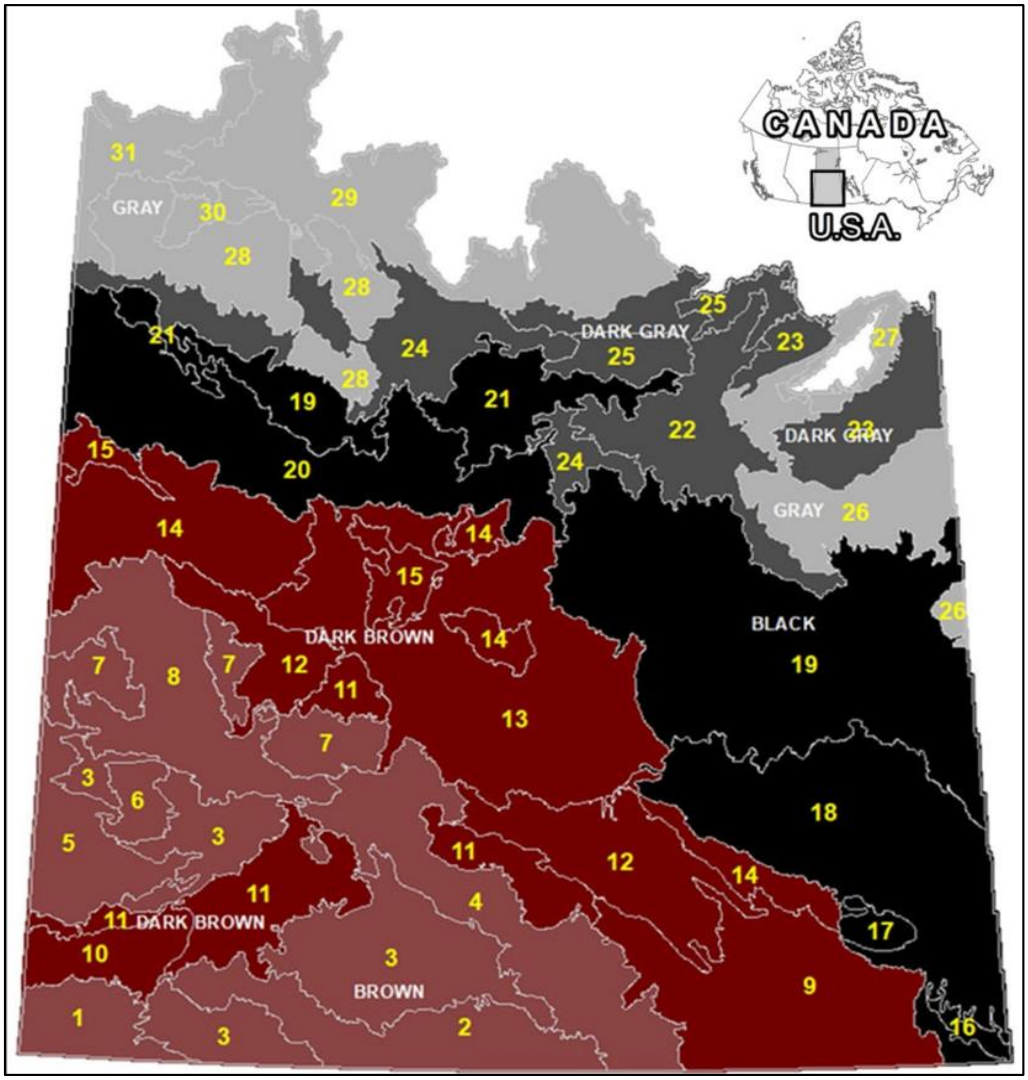

Figure 3.1 - Map of Saskatchewan depicting Soil Zone Ecodistricts (Amichev et al., 2017)

A tree mortality rate of 0% was used in this study as tree mortality is lowered in maintained shelterbelts than it is the case with a forest setting. This decision was based on personal communication with the principal investigator of AGGP, Professor Colin Laroque. Mortality rates for planted shelterbelt shrubs and trees is significantly reduced comparatively to forest trees. This is due to the presence of maintenance and direct care for the trees by the landowners (Laroque, 2019). However, some studies suggest mortality rates to be much higher than 0% (Amichev et al., 2016 and Government of Canada 2019a). Tree mortality rates are affected by conditions that may be influenced by climate change including drought or other extreme weather occurrences, or infestations of insects. Tree mortality has a direct effect on carbon balance as it is a loss of living trees, which are sequestering and storing C as well as dead trees releasing CO_2 during the process of decay (Government of Canada, 2019c).

The TEC t (tonnes) of carbon at different ages was calculated by taking the sum of TEC CO_2 that is sequestered by a km of shelterbelt annually over the number of years for a specific age. This was done through isolating the amount of carbon (expressed as CO_2) that is being sequestered annually by age of shelterbelt trees. The TEC values of carbon otherwise would begin as a positive value (carbon sink) as it included soil-locked carbon.

There are negative values for the first several years (0-17 years depending on species) of establishment for the TEC t CO_2 km yr for all soil zones and all species. Although the annual biomass rates (biom t CO_2 km yr) are positive as the tree and shrub species are growing, this value is miniscule as the trees are very small in size during the initial years of growth. The negative values are due to the dead organic matter (DOM), which consist of dead organic materials, soil and roots. Depending on the species of tree, a number of years (7-17) is required for the trees to grow crowns, branches and foliage, and establish their root systems. During this time, soil microbes are decomposing carbon continually; this results in a net soil carbon loss. Once these initial establishment years have passed, more aboveground growth occurs. The reasoning that the carbon cycling dynamic switches to a carbon sink is two-fold: increased aboveground biomass, and increased foliage and therefore shade, which decreases soil microbial carbon release. The TEC reaches a "breakeven" point after a number of years, once the biomass accumulation and therefore carbon accumulation reaches and surpasses the negative values created by the DOM. Following this, the DOM carbon reaches a breakeven point a number of years later once it stabilizes, reaches, and surpasses zero t CO_2 km yr. Finally, the DOM reaches a third breakeven point when it equates to the same amount of that of the TEC carbon (Amichev, 2019).

There are already existing carbon stores in soil prior to planting a shelterbelt, which will increase the carbon storage in both the soil (DOM) and within the biomass of the trees. The Black soil zone has higher amounts of pre-existing carbon stored. The Black soil zone is characterized by its higher levels of moisture and nutrient-rich soil, so this is expected. The Brown soil zone is more arid and less carbon-dense prior to planting shelterbelts.

3.3.3.2 Brown Soil Zone (BRN)

Chernozemic soils are found in the Brown, Dark Brown and Black soil zones of the prairies. There is a different amount of shelterbelts found in the different soil zones, for various reasons. One main reasoning behind more expected shelterbelt establishment in the Brown and Dark Brown soil zones comparatively to the Black soil zone (and grey and dark grey soil zones) is the aridity. Shelterbelts are often planted as a management practice in drier regions, which is characteristic of the Dark Brown and Brown soil zones. The expected total shelterbelt length (including all species) was 10,512 km for the Brown soil zone in 2015 (Amichev et al., 2014). There was generally less biomass in drier Brown soil zones, roughly 65% comparatively to that of the Black soil zone. Moisture availability is a key factor in the survivability and growth potential of a tree or shrub. This is the reasoning behind biomass accumulation in shelterbelt species typically being higher in the Black soil zone as the Brown soil zone in southwestern Saskatchewan. However, hybrid poplar was shown to be successful in scenarios of depressional areas[6], as its roots are capable of accessing ground water and therefore less affected by the aridity of the region (Kort and Turnock, 1999).

The Brown soil cluster 3 (BRN) contained the highest cumulative shelterbelt carbon stocks from the most recent shelterbelt inventory for the Brown soil clusters. The tree and shrub seedlings do not serve as a net carbon sinks in the first years. The species have different rates regarding the age they become a carbon sink. Manitoba maple becomes a carbon sink at age 5. Caragana becomes a carbon sink after age 6, and green ash, and scots pine, and hybrid poplar becomes a carbon sink at ages 5, 9 and 9, respectively. White spruce becomes a carbon sink only after 18 years due to its slow growth rate.

All species have a relatively steady increase of sequestration once they reach an age of 10 past establishment. Hybrid poplar yields the most carbon of the different species as it is the fastest growing species, and has a steady upwards trend of sequestration through ages 20 to 60. It also has the highest sequestration in this soil zone compared to the other species in all soil zones. White spruce has a slower rate of carbon sequestration in the first 20 years of growth; however it has similar values relative to Manitoba maple in its older ages. A table showing the values of the CO_2 sequestered by a kilometre of each species over 60 years, in increments of five years is

[6] A depression is any part of the Earth that is sunken in; specifically a low-lying area enclosed by elevated land (USDA, n.d).

displayed in Appendix B (Tables B.3 through B.5). In addition to these tables, tables B.6 through B.8, denote the CO_2 sequestration annually for the first 25 years, outlining when the species become carbon sinks (e.g., have a positive value for CO_2 sequestration).

3.3.3.3 Dark Brown Soil Cluster (DBRN_2)

As mentioned above, the Dark Brown soil cluster 13 (DBRN_2) contained the highest cumulative shelterbelt carbon stocks from the most recent shelterbelt inventory for the Dark Brown soil clusters. Intermediate level of biomass in shelterbelt growth was reported in Dark Brown soil zones, roughly 72% of that in the Black soil zone (Kort and Turnock, 1999). The expected total length of shelterbelts in the Dark Brown zone was just over four times the length of that in the Brown soil zone, at 45,231 km in 2015 (Amichev et al., 2014). The Dark Brown and Brown soil zones account for a significant amount more in total shelterbelt length compared to the combined numbers of the Black, grey and dark grey soil zones. The removal of shelterbelts occurs throughout all soil zones; however, a trend of removing them due to increased management costs and decreased benefits, was reported by landowners located mainly in the Black and Dark Brown soil zone (Amichev et al., 2014). The amount of TEC t CO_2 by age, in increments of five years and by species in the BRN is displayed in Figure 3.2.

Figure 3.3 depicts the TEC carbon sequestration in the DBRN_2 cluster in tonnes for a kilometre of shelterbelt per each species: caragana, green ash, hybrid poplar, Manitoba maple, Scotts pine, and white spruce. All species have a relatively steady increase of sequestration once they reach an age of establishment around year 10. As poplar species have very rapid growth, this is one of the reasons they are very efficient for carbon sequestration (Ball et al., n.d). This fact is borne out with the carbon sequestration rates shown in Figure 3.3 in comparison to other species. White spruce is a slow growing species; therefore it requires additional years to begin sequestering similar levels of carbon as the other species, however it is also a long living species, so the storage of carbon is extended as well (AAFC, 2015).

The tree and shrub seedlings do not serve as net carbon sinks in the first few years. Manitoba maple becomes a net carbon sink at age 5. Hybrid poplar, being the fastest growing species, yields the highest amount of carbon stored out of the six species with steadily increases in C storage through ages 20 to 60. White spruce has lesser incline of carbon sequestration to begin; however, it has values relative to Manitoba maple once it reaches and surpasses age 40 (Figure 3.3). The amount of carbon (expressed as CO_2) that a tree is capable of sequestering as it grows is dependent on the rate at which the tree grows and the amount of biomass it accumulates during its growth.

3.3.3.4 Black Soil Cluster (BLK_1)

All species have a relatively steady increase of sequestration once they reach an age of establishment around year 10. Manitoba maple shows the most rapid initial rate of sequestration and becomes a carbon sink before the other species. All species show a steady upward trend in their sequestration rates, with hybrid poplar sequestering the most carbon by far, of the six shelterbelt species. Figure 3.4 shows the tonnes of TEC CO_2 per km for each species of shelterbelt in the Black soil zone, in increments of five years.

3.4 Removal

3.4.1 Process of Removal

Removal of shelterbelts can be done a variety of ways. Landowners often either utilize equipment they already own, rent or borrow from a business or their local RM, or hire a company to do the removal for them. Commonly, some type of equipment, such as a skid-steer loader or bobcat with an attachment is utilized for this process. Shelterbelt Solutions, a shelterbelt and tree removal company based out of North Dakota, provided information on their shelterbelt removal process using skid-steer loaders and wheel loaders. They construct their own attachment for the removal, and utilize a grapple attachment for the cleanup. They rarely dig deeper than 0.91 m and the time required for removal varies dependent on the species itself, whether the trees are alive or dead, and length of shelterbelt/number of trees.

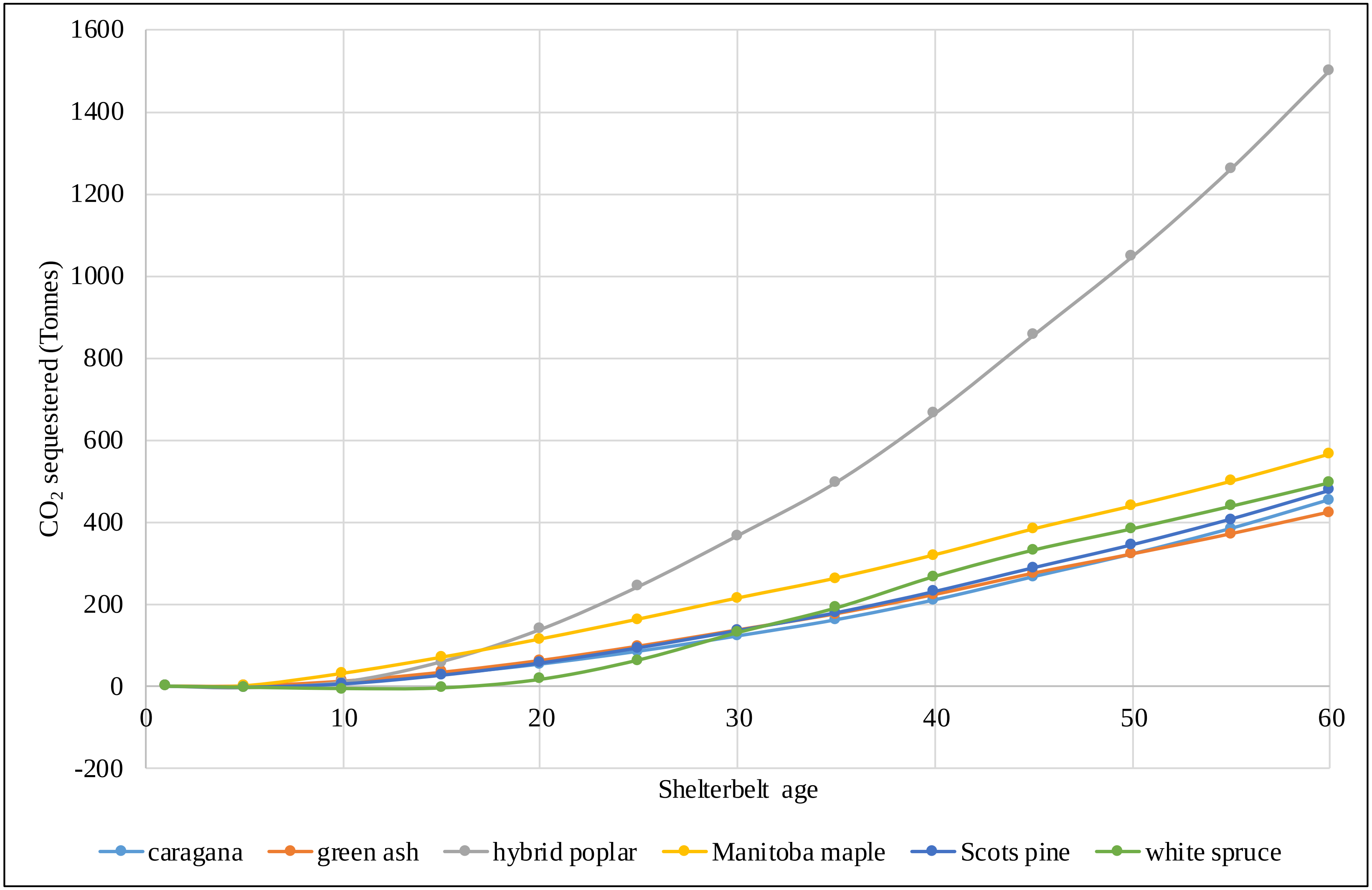

Figure 3.2 - TEC CO_2 in Tonnes per Species in the Brown Soil Zone, BRN Soil Cluster, with a Mortality of 0%, in Five-Year Increments

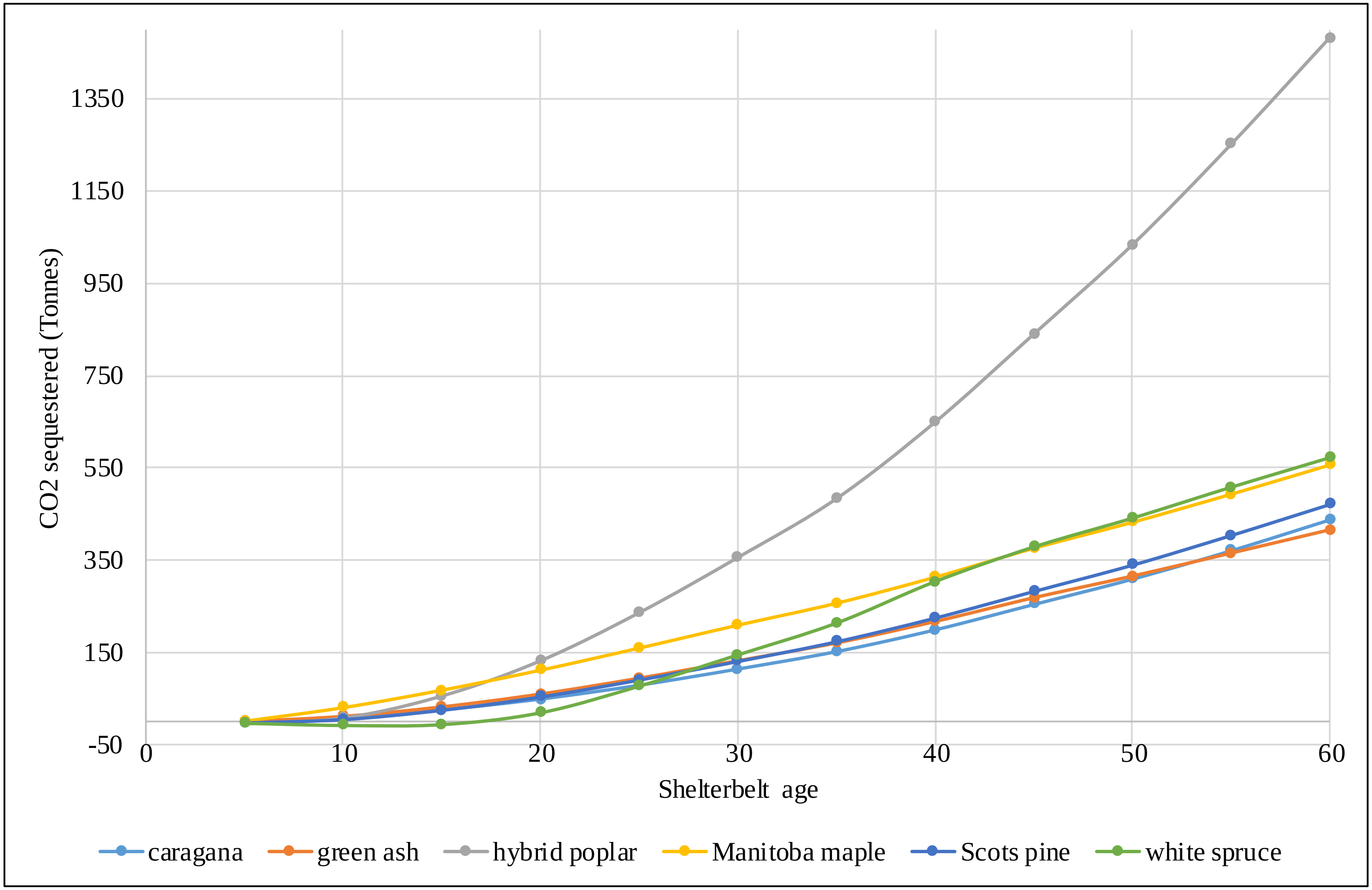

Figure 3.3 - TEC t CO_2 per Species in the Dark Brown Soil Zone, DBRN Soil Cluster, with a Mortality of 0%, in Five-Year Increments

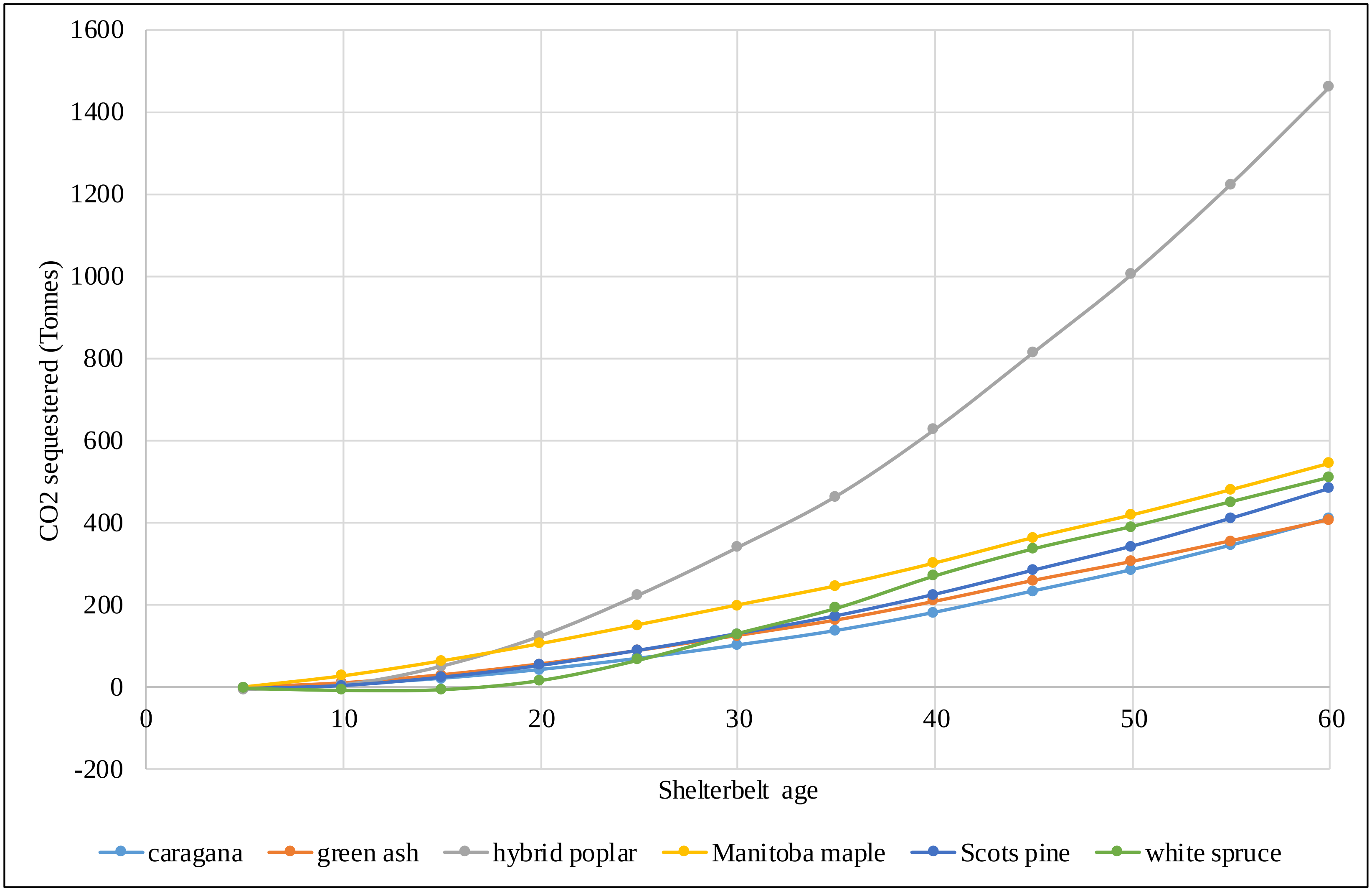

Figure 3.4 - TEC t CO_2 per Species in the Black Soil Zone, BLK Soil Cluster, with a Mortality of 0%, in Five-Year Increments

Information provided by the above company included machine hours for the removal of 805 m of different species: 30-40 hours of machine use to remove green ash trees; 20 hours to remove caragana; 40 hours to remove pine/spruce; 40-50 hours for smaller sized hybrid poplar; and 100-150 hours for larger hybrid poplars (Shelterbelt Solutions 2019). As the specifics of the equipment for removal are unknown, a proxy is utilized for this LCA. EcoInvent has data for an excavation style skid-steer loader (Appendix B.2), which can complete the task of removing the aboveground biomass and digging up the roots of the shelterbelt. This function is expressed by volume displaced (m^3). In order to calculate this value, the volume of earth displaced was estimated using the equation (3.4):

$$V\,(m^3) = Length\,(m) \times Width\,(m) \times Depth\,(m) \quad \ldots\ldots (3.4)$$

In this equation, the length is that of the functional unit, or one km (1000 m) and the depth is 0.91 m, as reported by Shelterbelt Solutions; for simplicity 1 m was assumed as the depth needed for removal. The width of excavation was not specified; however, it was assumed that it would be dependent on the tree species, or species category of shrub, coniferous and deciduous. However, a base value of soil displacement is utilized for the removal process in all LCA scenarios. A general width value of one m is used, as it is the minimum spacing recommended by shrub species when planting according to the AAFC (2010). Therefore, the volume displaced is shown in equation (3.5):

$$1000\,m \times 1\,m \times 1m = 1000\,m^3 \quad \ldots\ldots (3.5)$$

To account for the hours of equipment operation for removal, the EcoInvent proxy of a greater than 8.64 kW but less than 74.56 kW, low-load diesel machine operation (Appendix B – Table B.2) was used for the LCA. The equipment used included skid loaders and wheel loaders with attachments for the removal and grapple attachment for the cleanup. For reference, Cat skid steer loaders vary from 49.1 to 79.0 kW for net flywheel power, dependent on model utilized (Caterpillar, 2019). This function is measured on a dimension of time in hours. Therefore, time for removal for shrub shelterbelts is 20 hours; that for removal for coniferous and deciduous, including smaller sized hybrid poplar, is 40 hours; and removal for larger sized hybrid poplar is 125 hours (average of 100 to 150 hours). As the time required to complete these removals were reported by Shelterbelt Solutions in increments of 0.805 km, these times were multiplied by 0.805 in order to convert to one km measurements. Therefore, removal of a km of shrub requires an estimated 25 hours, and removal of coniferous/deciduous/small poplars and larger sized hybrid poplars require 50 hours and ~156 hours, respectively.

3.4.2 Loss of Carbon Post Removal

Conventional land clearing has included the removal, piling and burning of the dead woody biomass of shelterbelts (Dobb, 2013). Alternatively, the wood from the removed shelterbelt can be used for production of wood products (Sheth, 2017); however, this is rarely a cost effective method for the end of life stage for landowners. For the purposes of this study, the common removal method of burning the removed biomass was assumed. In this process, it was assumed that 100% of the aboveground biomass carbon will be released as CO_2 into the atmosphere. The carbon stored within the remaining roots and surrounding soil is not immediately released; however, a slow release of CO_2 occurs through autotrophic respiration of roots and heterotrophic respiration of soil organisms (Bond-Lamberty, 2004). The remaining stored carbon was determined using the loss of all aboveground biomass and stem carbon values being lost immediately during the burn, and an annual decrease of dead organic matter carbon (DOM) stores following the removal and burn process. This is assuming that the land is left following the removal. If there are to be crops planted in place of the shelterbelt, the emissions from the soil would increase due to presence of machinery.

3.5 Results

The life cycle stages at the farm level consist of planting, maintenance (herbicide, fertilizer, irrigation and tillage — HFIT), life in field (years of establishment of carbon sequestration/storage) and end of life (removal). The methods and inputs for each life cycle stage were outlined in this Chapter to assess GHG emissions (only CO_2) from all the components of the life of planting and aiding a shelterbelt to survive and thrive as a beneficial management practice on agricultural landscapes. All of the inputs for each stage were accounted for and entered in the LCA software program SimaPro. The method or lens in which the data was observed, analyzed and calculated was Select LCI. This method produces CO_2 emissions associated with the whole life cycle stage, as well as broken down by individual inputs. This is useful to target the higher emitting inputs in the production process (inventory) required for shelterbelt seedling establishment. In addition to outlining this, the first half of the complete LCA including the production and transporting as covered in Chapter 2 was completed. In the following sections, the CO_2 emissions from planting, maintenance, and removal are covered for different shelterbelt planting scenarios (a one km shelterbelt of coniferous, deciduous, and shrub species). Finally the CO_2 lost following removal due to shelterbelt biomass becoming a waste product (i.e., burning), as well as the steady loss of CO_2 form soil carbon stores in a scenario void of replanting a shelterbelt are outlined.

3.5.1 Planting

The preparation of the land for planting consists of tilling in order to prepare the soil as a preliminary weed control. The area of land being tilled is equal for the three tree variety categories (coniferous, deciduous, and shrub) as shown in Table 3.1.

Table 3.1 - CO_2 Produced by Planting Life Stage by Species Category

Phase step	Impact Category	Unit	Coniferous	Deciduous	Shrub
Tillage	Carbon dioxide	t	0.01	0.01	0.01
Planting	Carbon dioxide	t	0.53	0.76	1.90
Total	Carbon dioxide	t	0.53	0.77	1.91

3.5.2 Monte Carlo Uncertainty Analysis

An uncertainty analysis was conducted utilizing the Monte Carlo simulation within the SimaPro software to determine uncertainty and risk in the planting emissions results. Table 3.2 reports the mean, median, standard deviation, coefficient of variation, the 2.5% and 97.5% percentiles and standard of error mean of planting emissions. Figure 3.5 displays the high-low uncertainty range of the CO_2 emissions at the 95% confidence interval. The mean and median for the CO_2 produced by the planting of seedlings is equal to 488 kg and 535 kg, respectively, and are shown as the dashed blue vertical line and solid blue vertical line (Figure 3.5). The two red vertical lines denote the borders for the 95% confidence interval, where the 2.5% percentile is at 224 kg CO_2 and the 97.5% percentile is at 1,110 kg CO_2.

Table 3.2 - Monte Carlo Uncertainty Analysis for the CO_2 Emissions for Planting of 277 Seedlings with 95% Confidence Interval

Category	Carbon dioxide (kg)
Mean	488
Median	535
Standard Deviation	223
Coefficient of variation (%)	41.8
2.5%	224
97.5%	1,110
Standard error of the mean	7.05

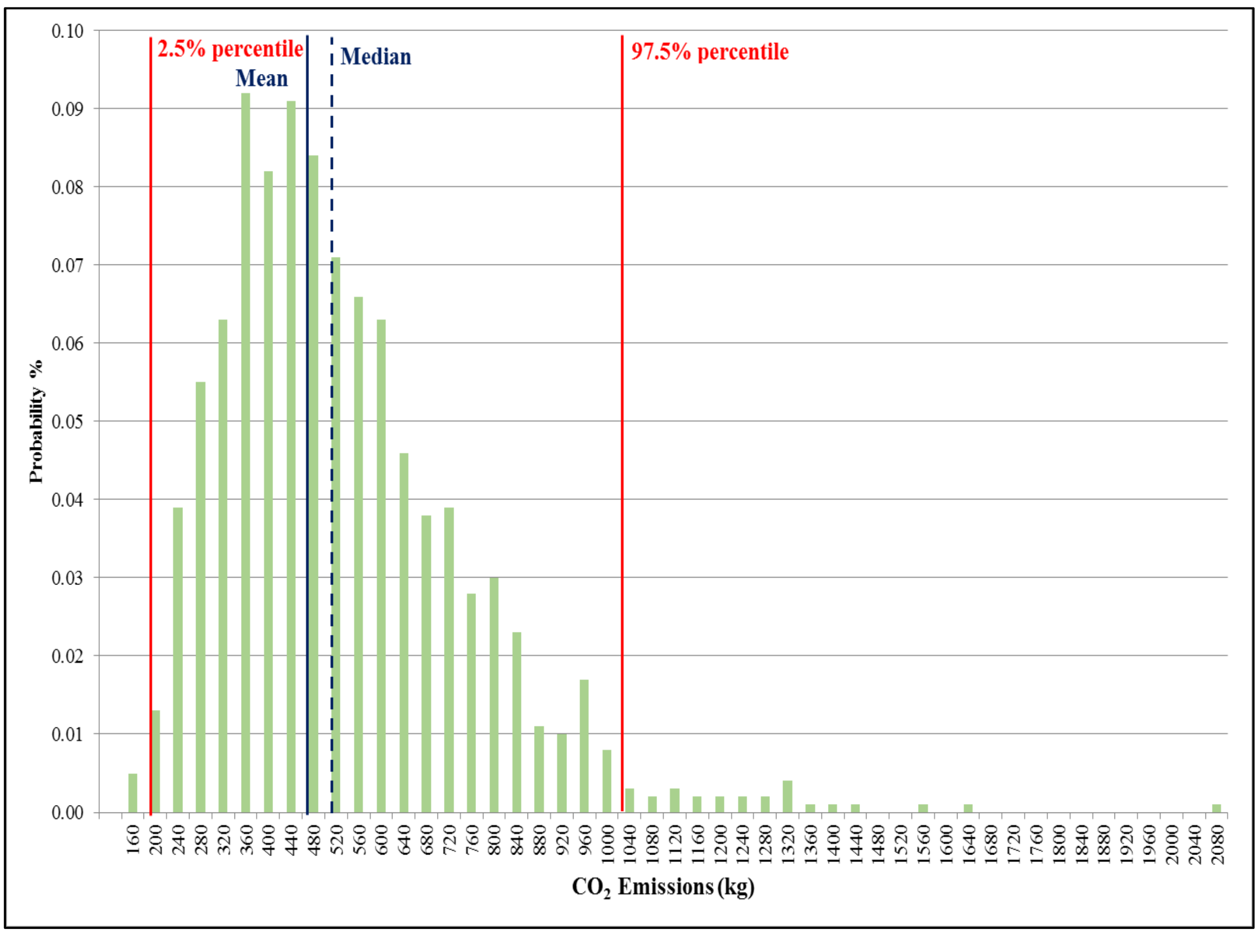

Figure 3.5 - Monte Carlo Uncertainty Analysis for the Total CO_2 Emissions for Planting of a Coniferous Shelterbelt (277 seedlings) with 95% Confidence Interval

The probability of the mean, the predicted value for 535 kg CO_2 emissions produced by SimaPro is slightly above 9%, and falls below the median of the bell curve. The highest probability, slightly above 9%, for a CO_2 emission was 360 kg. Figure 3.5 shows that there is 95% chance that the actual value for CO_2 emissions from the planting of seedlings will fall within the range of 224 to 1,110 kg per km of shelterbelt.

3.5.3 Maintenance

3.5.3.1 Nature of Maintenance of Shelterbelts

The maintenance level is based on recommended HFIT applications. Minor emissions may occur from the slight agitation of soil when the seedlings are planted, but the amount of emissions created are negligible. Although specific quantitative data on the correlation between maintenance and the amount of carbon sequestered by shelterbelt species was not included in this study, there may be a correlation between survivability of shelterbelt species and maintenance applied. Any portion of a shelterbelt that does not survive will not sequester and the amount of stored carbon is limited. This points out that the maintenance is important for success of shelterbelts being able to sequester carbon. Figure 3.6 shows the breakdown of CO_2 emissions in tonnes by HFIT category for a kilometre long shelterbelt (applicable of any species).

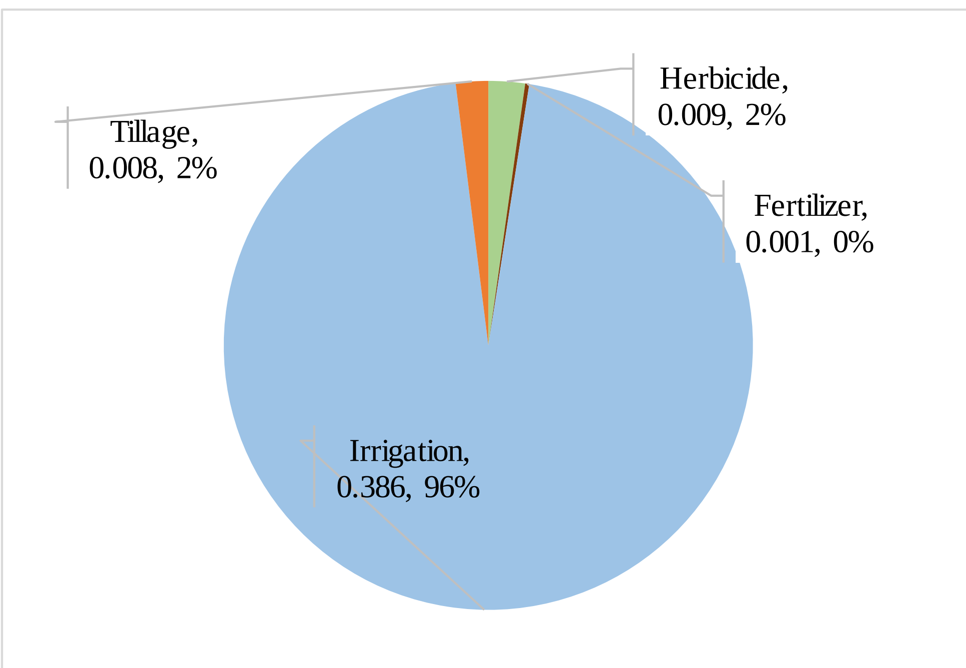

Figure 3.6 - CO_2 Emissions in Tonnes Produced in Maintenance Phase

3.5.3.2 Monte Carlo Uncertainty Analysis

An uncertainty analysis was conducted utilizing the Monte Carlo simulation within the SimaPro software to determine uncertainty and risk in the results associated with different levels of maintenance applied to the shelterbelts. Figure 3.7 displays the high-low uncertainty range of the CO_2 emissions at the 95% confidence interval.

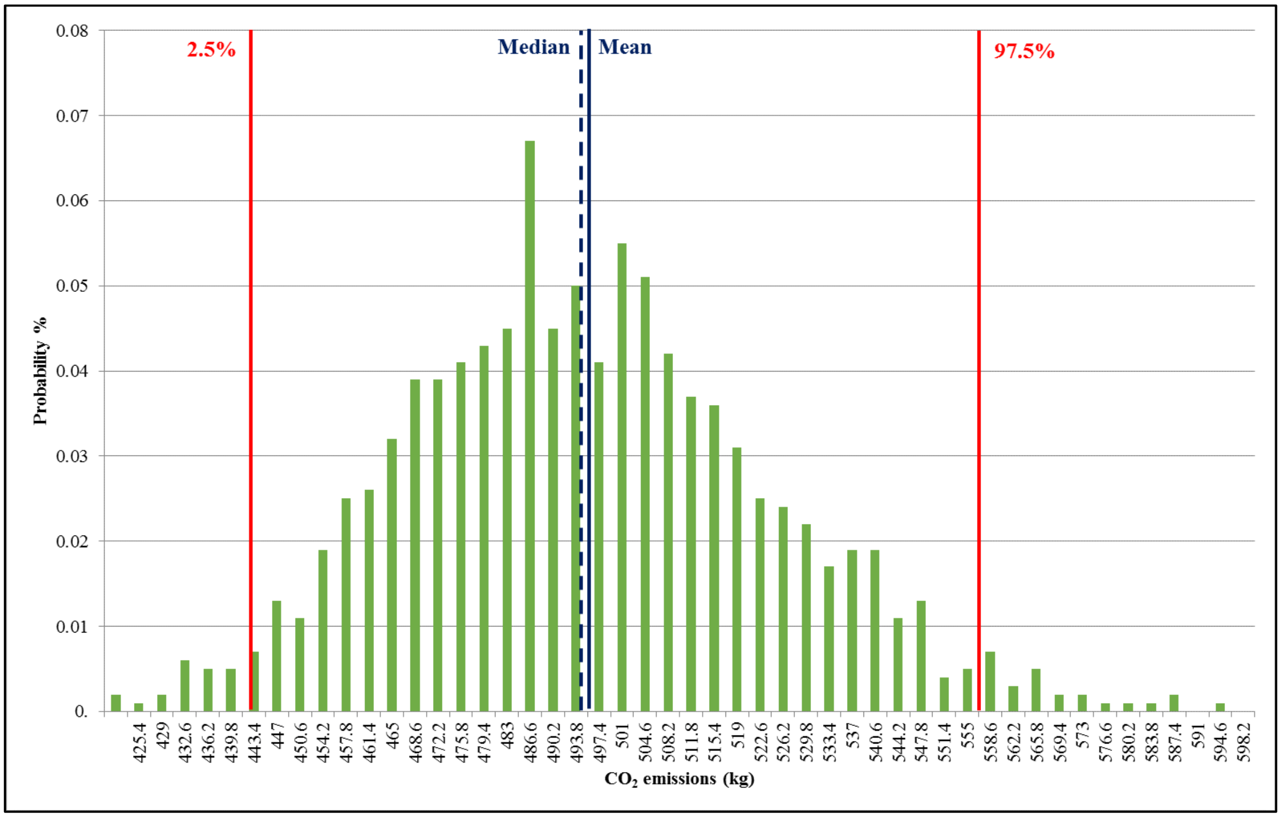

Figure 3.7 - Monte Carlo Uncertainty Analysis for the total CO_2 Emissions for the Maintenance of a km Shelterbelt with 95% Confidence Interval

As reported in Table 3.3 and Figure 3.7, the mean and median for the CO_2 produced for the maintenance phase equal to 494 kg and 496, and are shown as the dashed blue vertical line and solid blue vertical line in Figure 3.7. The two red vertical lines denote the borders for the 95% confidence interval, where the 2.5% percentile is at 433 kg CO_2 and the 97.5% percentile is at 557 kg CO_2. Based on the uncertainty values on reliability, completeness, geographical correlation, temporal correlation, and technological correlation of each input found at the LCA stage, a probability for the CO_2 emissions is outputted using the Monte Carlo function. The probability of the mean, the predicted value for 494 kg CO_2 emissions produced by SimaPro is slightly above 6%, the exact value of the median of the bell curve. Figure 3.7 shows that there is 95% chance that the actual value for CO_2 emissions from the planting of seedlings will fall within the range of 433 to 557 kg per km of shelterbelt.

Table 3.3 reports the mean, median, standard deviation, coefficient of variation, the 2.5% and 97.5% percentiles and standard of error mean for the emissions produced during the maintenance phase of the life cycle.

Table 3.3 - Monte Carlo Uncertainty Analysis for the Total CO_2 Emissions for the Maintenance of a km Shelterbelt with 95% Confidence Interval

Category	**Carbon dioxide (kg)**
Mean	494
Median	496
Standard Deviation	28.6
Coefficient of variation (%)	5.77
2.5%	443
97.5%	557
Standard error of the mean	0.904

3.5.4 Removal

3.5.4.1 Level of carbon lost by species

The removal scenario is outlined in this section using information provided from a shelterbelt removal company — Shelterbelt Solutions. The CO_2 emissions attributable to the machinery used for the removal of a one kilometre long shelterbelt for the three different shelterbelt categories: shrub, coniferous and smaller sized deciduous, and larger sized deciduous (large hybrid poplars) are presented in Table 3.4.

The estimated amount of CO_2 produced in the removal of a caragana (as well as for coniferous— white spruce and Scots pine) shelterbelt would equate 0.82 t, and for deciduous (green ash, small to medium hybrid poplar, and Manitoba maple) at 1.12 t for large hybrid poplars. Some stands of hybrid poplars can grow very large, and in these cases, up to 2.43 t CO_2 or more can be sequestered during this process (Table 3.4). These required machine hours were based on the size, composition, and age of the trees. There is an increased amount of biomass found in shelterbelts of coniferous and deciduous trees, relative to shrub shelterbelts, and even more so in larger deciduous shelterbelts (namely old growth hybrid poplars). The latter requires more machine hours: trimming, chainsaw, skid-steer loader with attachment for pushing trees and pulling up roots. More machine hours equate more fossil fuels being burned and more CO_2 being released. In addition to this, removing larger and older shelterbelts will release more stored carbon when the removed biomass is eventually burned, as is common practice after shelterbelt removal.

Table 3.4 - CO_2 Produced by Removal of One km Shelterbelt by Species Category in Tonnes

Shelterbelt Type	**Operation**	**Amount**	**Unit**	**CO_2 produced**
Shrub	Excavated land	1,000	m^3	0.51
	Machine operation	25	Hrs.	0.31
	Total			0.82
Coniferous and Deciduous	Excavated land	1000	m^3	0.51
	Machine operation	50	Hrs.	0.62
	Total			1.12
Large hybrid poplars	Excavated land	1,000	m^3	0.51
	Machine operation	155	Hrs.	1.92
	Total			2.43

3.5.4.2 Monte Carlo Analysis

An uncertainty analysis was conducted utilizing the Monte Carlo simulation within the SimaPro software to determine uncertainty and risk in the carbon emissions attributable to shelterbelt removal results. Figure 3.8 displays the high-low uncertainty range of the CO_2 emissions at the 95% confidence interval. As reported in Table 3.5 and Figure 3.8, the mean and median for the CO_2 produced by removing a one km shelterbelt of coniferous or deciduous trees is equal to 902 and 901 kg, respectively, and are shown as the dashed blue vertical line and solid blue vertical line in Figure 3.8. The two red vertical lines denote the borders for the 95%

confidence interval, where the 2.5% percentile is at 661 kg CO_2 and the 97.5% percentile is at 1,233 kg CO_2.

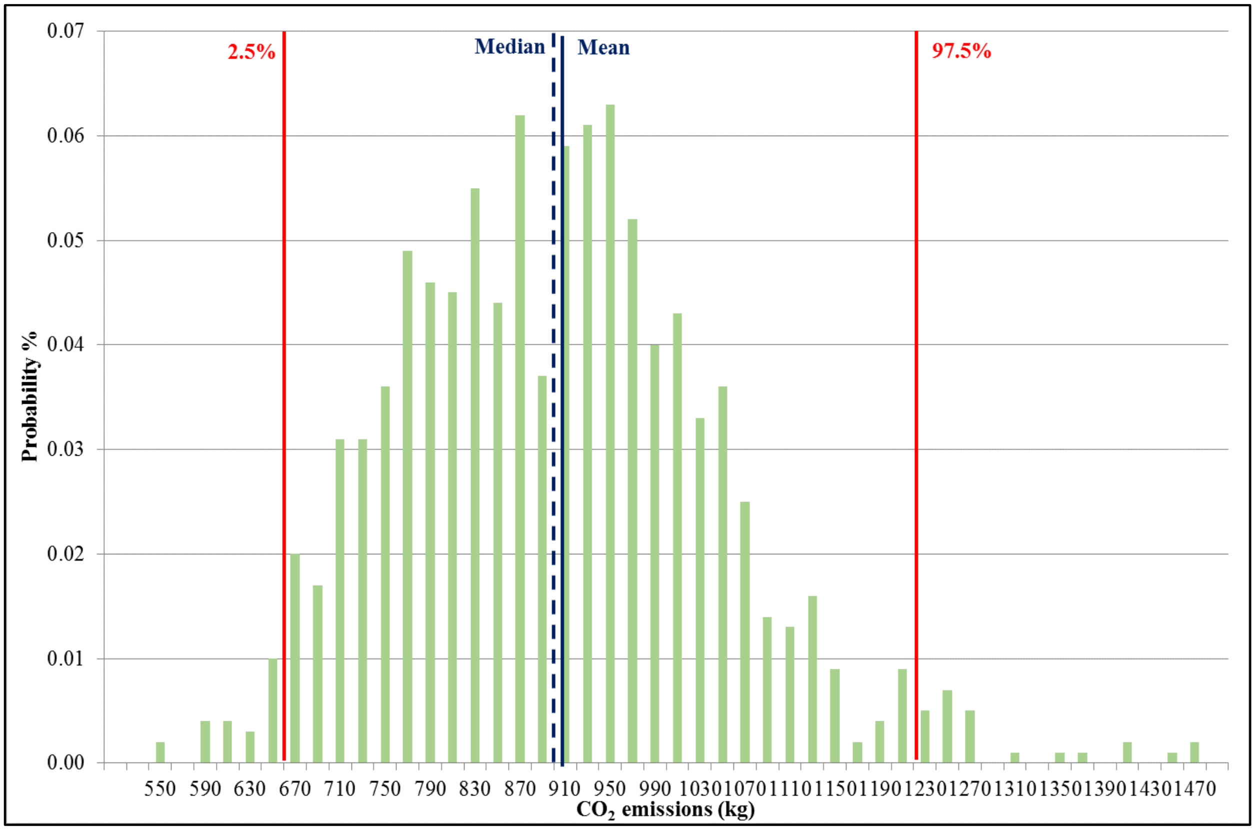

Figure 3.8 - Monte Carlo Uncertainty Analysis for total CO_2 Emissions for the Removal of a km Coniferous/Deciduous Shelterbelt with 95% Confidence Interval

Table 3.5 reports for the emissions of shelterbelt removal, the mean for the removal of a medium coniferous/deciduous shelterbelt, median, standard deviation, coefficient of variation, the 2.5% and 97.5% percentiles and standard of error mean.

Based on the uncertainty values on reliability, completeness, geographical correlation, temporal correlation, and technological correlation of each input found at the LCA stage, a probability of a value for the CO_2 emissions was estimated is using the Monte Carlo function, as shown in Table 3.5 and Figure 3.8. The probability of the mean, the predicted value for 902 kg CO_2 emissions produced by SimaPro is slightly below 6%. The highest probability, slightly above 6%, for a CO_2 emission was 950 kg. Figure 3.8 shows that there is 95% chance that the actual value for CO_2 emissions from the removing a shelterbelt of coniferous or deciduous trees will fall within the range of 661 to 1,223 kg per km of shelterbelt.

Table 3.5 - Monte Carlo Uncertainty Analysis for the Total CO_2 Emissions for the Removal of a km Coniferous/Deciduous Shelterbelt with 95% Confidence Interval

Category	**Carbon dioxide (kg)**
Mean	902
Median	901
Standard Deviation	141
Coefficient of variation (%)	15.7
2.5%	661
97.5%	1,223
Standard error of the mean	4.47

3.5.4.3 Soil Related Loss of Carbon following Removal

The carbon stocks for shelterbelt species were measured and distinguished by TEC (total ecosystem carbon), stems, and DOM (dead organic matter). The DOM C (Dead organic Matter Carbon), including the carbon originally in the soil prior to planting the shelterbelt, makes up 37% to 50% of the TEC. Planting vegetation fixes carbon into the soil. The preexisting carbon stored in the soil prior to planting a shelterbelt is a result from previous vegetation and decaying organic matter. The DOM C pool remains for a number of decades following the removal of the shelterbelts. However, the carbon stocks that result from the shelterbelt are a component of a constant carbon flux; including air-to-biomass, biomass-to-soil, and soil-to-air (Schlesinger and Andrews, 2000). Following the removal of the shelterbelt, there are no longer any trees to fix the CO_2 into the biomass and soil; however the soil-to-atmosphere exchange is still occurring. It is important to note that some of this carbon already existed in the soil even prior to planting the shelterbelt, as the soil biome is an important carbon sink, and that anthropogenic activities such as the planting or removal of shelterbelts and applied disturbance versus conservation of soils can impact the process of carbon storage or loss (Ontl and Shulte, 2012).

In addition to the emissions of CO_2 during the removal process, the carbon stored in the biomass of the trees is released upon burning. This study assumes that 100% of the carbon stored in the biomass is released as CO_2. The Table 3.6 shows show the TEC C and CO_2 values for a 60 year old shelterbelt, which includes the biomass and DOM carbon, the amount of stored carbon in the biomass lost during the removal, and the remaining stored carbon in the soil (DOM) for the Brown, Dark Brown, and Black soil zones.

Brown Soil Zone: The Brown soil zone is characteristic of being arid and containing a large complement of shelterbelts in Saskatchewan, second to the Dark Brown soil zone. The Brown soil zone showed the smallest pre-existing DOM carbon stores of the three soil zone clusters. The Brown soil zone cluster also has the least remaining carbon (expressed as CO_2) of the three soil clusters following the removal of biomass. The biomass of a 60 year old caragana shelterbelt accounts for 42% of the TEC t CO_2 in the BRN soil cluster. The percentages that the biomass accounts for TEC t CO_2 of a 60 year old shelterbelt of green ash, hybrid poplar, Manitoba maple, Scots pine, and white spruce is 50%, 63%, 52%, 56%, and 58%, respectively. Following the removal of the biomass and release of biomass-locked carbon, the shelterbelt areas are left with the DOM carbon, as outlined in the right column of Table 3.6.

Table 3.6 - CO_2 Values in Tonnes of TEC, Biomass CO_2 Loss Post Removal, Remaining DOM CO_2 for Brown Soil Zone, BRN Soil Cluster

	TEC CO_2 km (biomass & DOM) at age 60	**Biomass CO_2 loss following removal at age 60**	**Remaining DOM CO_2**
Caragana	739.98	310.75	429.23
Green ash	624.75	310.49	314.26
Hybrid poplar	1,922.51	1,204.83	717.68
Manitoba maple	755.75	395.79	359.96
Scots pine	723.64	407.59	316.05
White spruce	731.93	425.97	305.96

Figure 3.9 displays the amount of carbon (expressed as CO_2) that remains over the 100 years following the removal of a kilometre shelterbelt of each species in the Brown, BRN soil cluster. The annual DOM CO_2 loss for caragana, green ash, hybrid poplar, Manitoba maple, Scots pine, and white spruce in this scenario (BRN) is -0.94, -0.66, -1.39, -0.63, -0.81, and -0.66,

respectively (Amichev, 2019). Note this is representative for soils that is mostly undisturbed. Soil that is worked or tilled would have an increased amount of CO_2 loss to the atmosphere.

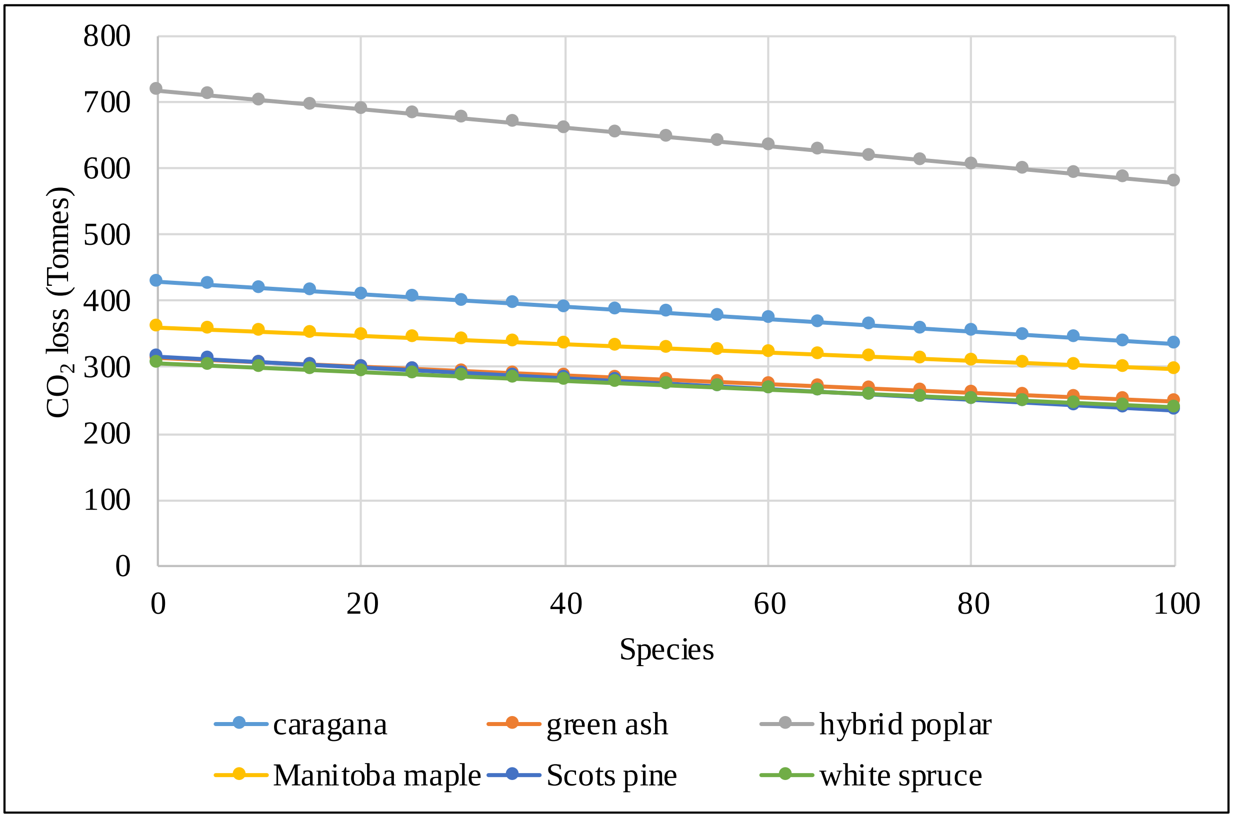

Figure 3.9 - Tonnes of CO_2 Loss per km from DOM in Years Following Removal of Shelterbelt by Species for Brown Soil Zone, BRN Soil Cluster

The loss in carbon is steady over time as it is assumed that the soil locked carbon to atmospheric CO_2 dynamic releases roughly at the same rate annually. Following the removal of trees, the DOM previously associated with a shelterbelt of caragana would lose 94.08 tonnes of CO_2 over the course of 100 years. In the case of green ash, 66.01 t CO_2 are lost to the atmosphere from the soil over 100 years. Hybrid poplar sees the most dramatic carbon loss; however, it also has the largest carbon storage of the six species, and loses 139.27 t CO_2 100 years following removal. Manitoba maple, Scots pine and white spruce will lose an additional 62.68 t CO_2, 81.35 t CO_2 and 66.24 t CO_2, respectively, over 100 years following removal (Appendix B – Tables B.9 through B.11).

This study did not include a method, such as an automated soil chamber, to precisely measure this loss of carbon. In order to account for this, the best assumption of the amount of carbon lost to the atmosphere following the lack of previous trees is to refer to the rate of carbon lost as CO_2 prior to tree being planted. Although hybrid poplar loses the most CO_2, by tonne proportionately it loses CO_2 slower than the other species, save for Manitoba maple at 17% carbon loss; hybrid poplar loses roughly 19%. Caragana, green ash, and white spruce all lose roughly 21-22% of their DOM carbon stores over 100 years and Scots pine sees the largest loss, at roughly 25% DOM carbon lost in the century.

Dark Brown Soil Zone: The Dark Brown soil zone cluster shows less soil-locked carbon (DOM) loss following the removal of the shelterbelt biomass (i.e., trees) than the Brown soil zone. This is due to more carbon being sequestered as DOM in this soil zone, as is evident by the fact that the amount of CO_2 lost from biomass removal is almost the same in both the Brown and Dark Brown soil zones. The breakdown of TEC CO_2 km, biomass and DOM, loss of CO_2 due to the removal of biomass, and remaining DOM CO_2 values are shown in Table 3.7. The biomass accounts for 38% of the TEC t CO_2 for a 60 year old shelterbelt of caragana in the DBRN soil cluster. The biomass of a 60 year old shelterbelt comprised of green ash accounts for 46% of the TEC t CO_2. The percentages that the biomass accounts for TEC t CO_2 of a 60 year old shelterbelt of hybrid poplar, Manitoba maple, Scots pine, and white spruce are, respectively, 60%, 49%, 52%, and 58%, respectively.

A significant amount of carbon from the TEC value remains locked in the soil (62%, 54%, 40%, 48%, and 42% respectively for caragana, green ash, hybrid poplar, Manitoba maple, scots pine and white spruce) following the removal of the biomass; therefore the carbon storage is not completely voided immediately during the removal. However, this removal influences a change in the carbon dynamic as there is no longer biomass to fix the atmospheric CO_2 and the microbial activity in the soil will slowly release this stored carbon back into the atmosphere over a number of years. As mentioned for the Brown soil zone, the loss of carbon following the removal of biomass is steady as an assumed fixed rate for annual CO_2 loss for each species. The release in carbon as CO_2 from the DOM storage in years following removal is displayed in Figure 3.10 and can be seen in detail in Appendix B.9.

Table 3.7 - CO_2 Values in Tonnes of TEC, Biomass CO_2 Loss Post Removal, Remaining DOM CO_2 for Dark Brown Soil Zone, DBRN_2 Soil Cluster

	TEC CO_2 km (biomass & DOM) at age 60	**Biomass CO_2 loss following removal at age 60**	**Remaining DOM CO_2**
Caragana	801.37	307.23	494.13
Green ash	671.41	310.09	361.32
Hybrid poplar	2,022.27	1,204.12	818.15
Manitoba maple	798.81	394.19	404.62
Scots pine	785.39	411.07	374.32
White spruce	873.87	508.81	365.06

The CO_2 lost via removal of biomass is slightly less than that of the Brown and Dark Brown soil zones, due to a higher percentage of CO_2 locked as DOM carbon. The biomass of a 60 year old caragana shelterbelt accounts for 36% of the TEC Mg C in the BLK soil cluster. The percentages that the biomass accounts for TEC t CO_2 of a 60 year old shelterbelt of green ash, hybrid poplar, Manitoba maple, Scots pine, and white spruce is 44%, 57%, 47%, 50%, and 53%, respectively. Following the removal of the biomass and release of biomass-locked carbon, the shelterbelt areas are left with the DOM carbon, as outlined in the right column of Table 3.8.

Black Soil Zone: The Black soil zone cluster shows the highest amount of pre-existing DOM carbon stores prior to planting the shelterbelts, as is characteristic of the high nutrient, carbon-rich, and high moisture soil zone. The CO_2 lost via removal of biomass is less than that of the Brown and Dark Brown soil zones, due to a higher percentage of CO_2 locked as DOM carbon (Table 3.8).

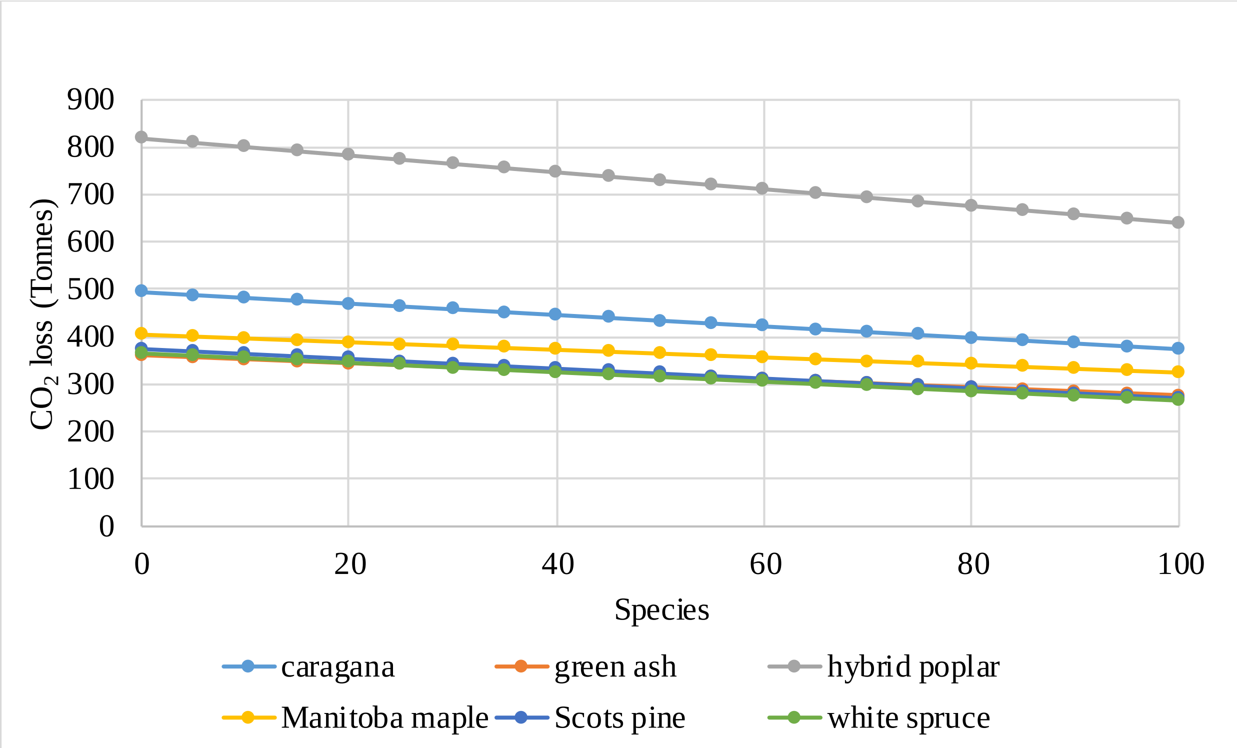

Figure 3.10 - Tonnes of CO_2 Loss per km from DOM in Years Following Removal of Shelterbelt by Species for Dark Brown Soil Zone, DBRN Soil Cluster

Table 3.8 - CO_2 Values in Tonnes of TEC, Biomass CO_2 Loss Post Removal, Remaining DOM CO_2 for Black Soil Zone, BLK Soil Cluster

	TEC CO_2 km (biomass & DOM) at age 60	**Biomass CO_2 loss following removal at age 60**	**Remaining DOM CO_2**
Caragana	832.51	296.02	536.49
Green ash	703.47	308.12	395.35
Hybrid poplar	2,085.75	1,196.44	889.31
Manitoba maple	825.81	389.43	436.38
Scots pine	848.36	428.20	420.16
White spruce	859.94	451.93	408.01

The quantity of carbon (expressed as CO_2) that remains in the soil 100 years following the removal of a kilometre of shelterbelt for each tree species in the Dark Brown, BLK soil cluster, with a mortality of 0% is reported in Figure 3.11. The annual DOM CO_2 t loss for caragana, green ash, hybrid poplar, Manitoba maple, Scots pine, and white spruce in this scenario (BLK) is -1.39, -0.98, -2.06, -0.93, -1.20, and -0.98, respectively.

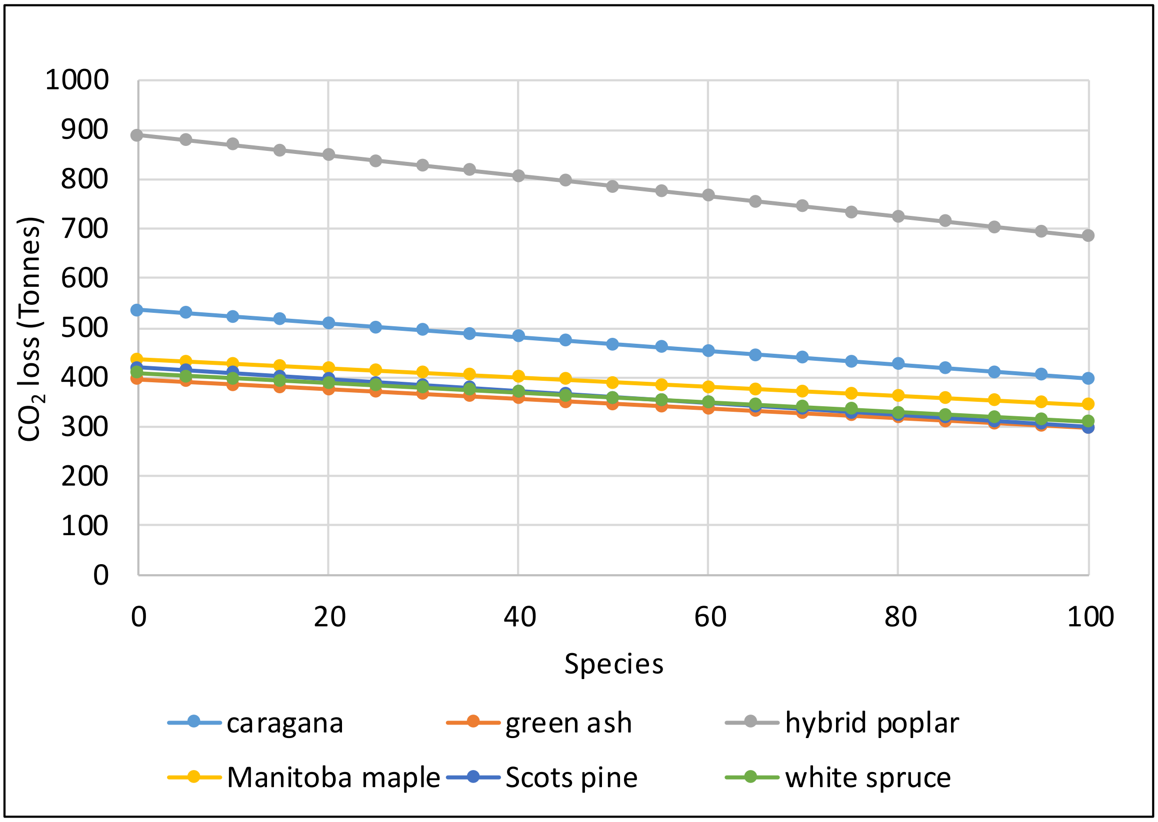

Figure 3.11 - Tonnes of CO_2 Loss per km from DOM in Years Following Removal of Shelterbelt by Species for Black Soil Zone, BLK Soil Cluster

3.5 Discussion

The purpose of this study was to outline the inputs (full list in Appendix B - Table B.1 and Table B.2) required for each life cycle stage following the production and transportation of seedlings to farm. Additionally, this study research analyzed the data from the inventory of inputs to create a carbon footprint for the life cycle stages, using software program SimaPro. A broad application of life phases was applied as a general base for all shelterbelt species. These values may differ from species to species, but in general, they follow a similar process for planting and establishing a shelterbelt of any species.

The life cycle stage of preparation and planting includes tilling the land and planting the seedlings. The tilling component was assumed to be consistent for all three types of shelterbelt (coniferous, deciduous and shrub), as it is based on the functional unit of a kilometre length of land (with an area of 1000 m^2). The difference in CO_2 emissions between types of tree for this life cycle stage included the different requirement for number of seedlings planted. Planting accounts for more of the CO_2 production in the life stage, equating roughly 99% of the CO_2 produced. Roughly 0.53 t of CO_2 is produced to prepare the land and plant a km long shelterbelt of conifer seedlings, and 0.76 t and 1.90 t of CO_2 is produced to plant deciduous and shrub shelterbelts The biggest impact on the emissions in the planting stage is the number of seedlings planted; however, this being said, the more seedlings planted, staying within recommended spacing requirements, the more CO_2 sequestered during the growth of the shelterbelt shrub and tree species. Note that this study assumed that a mechanical tree planter was involved as was commonly reported in the survey administered over the 2017/2018 field seasons. However, planting by hand was reported to be a common method of planting as well and this method of planting would decrease the emissions released at this stage. The trade-off would increase manual labor cost and time comparative to the planting using the tree-planter equipment. Regardless of planting method, the CO_2 emissions associated with planting the seedlings is miniscule in comparison of CO_2 sequestered once the trees are established and grow. The maintenance life cycle stage included the HFIT (herbicide, fertilizer, irrigation, and fertilizer) components. The high level of maintenance was based on recommendations of HFIT applications by a variety of agriculture and arborist literature. The percentages that the HFIT (of high level maintenance) components comprise for the 0.494 t of CO_2 produced by this life cycle stage are 18%, 0.03%, 78%, and 0.02% for herbicide, fertilizer, irrigation and tillage. It is important to note that fertilizer is a high emission producing input, however the miniscule amount required for a shelterbelt comparable to a crop, does not emphasize this as such.

Although there was no specific research work done under the purview of this study to highlight the exact correlation between maintenance applied and growth of shelterbelt trees, maintenance is important for the survival and success of trees. In a scenario where very few trees survive in the shelterbelt, the amount of CO_2 that is sequestered is significantly smaller. Proper shelterbelt design and maintenance that is appropriate to the timing of growth and regional conditions, is key for shelterbelt success and benefits (Kort, 1988). Proper moisture is important for the establishment of tree seedlings, especially in regions that are more arid, such as the Brown soil zone. The use of irrigation for shelterbelts may be more common in these arid regions or in drier years in all soil zones. Some tree species, such as the hybrid poplar, are efficient at seeking ground water via their roots system and may be less impacted by these dry conditions (Kort and Turnock, 1999). Green ash and caragana are also known for their drought-tolerant capabilities (AAFC, 2007). Competition by weeds for light and soil moisture and nutrients can be harmful to tree seedlings as they establish in their initial years of growth. This is specifically a risk in the Brown and Dark Brown soil zones where moisture may already be a limited resource. Infestations of annual weeds of a moderate severity can reduce the growth in tree and shrub seedlings by 50-75 % (Esau, 2007). Applying herbicides to stunt the growth of these weeds, so that the shelterbelt seedlings have the opportunity to establish, can be very important for their success. Tillage is also used for weed management prior to and after planting seedlings. Shelterbelts do not require fertilizer if they are a healthy or growing in high nutrient soils; however, in regions where the soil is nutrient-deprived, the application of fertilizer can be beneficial for the success of shelterbelts planted there (AAFC, 2007).

Hybrid poplar had the highest level of carbon stored of the six species in all three soil zone clusters with 1,500.50 t CO_2 being sequestered by a km shelterbelt in the Brown soil zone (BRN). The carbon storage by hybrid poplar shelterbelts in the Dark Brown and Black soil zone clusters were slightly less than that of the Brown soil zone cluster at 1,482.80 and 1,461.39 t CO_2, respectively. The Brown soil zone has typically more arid and less nutrient dense soils compared to the Dark Brown and Black soil zones, resulting in a decrease in the amount of expected biomass. However, this was not the case for hybrid poplar, which showed the highest biomass and carbon sequestration by age 60 in the Brown soil zone. Caragana, green ash, Manitoba maple and scots pine all reported a slightly higher biomass and carbon sequestration in the Brown soil zone relative to other soil zones. White spruce was the only species that reported a higher biomass and carbon sequestration in the Dark Brown soil zone, and lower amount in the Brown soil zone. This may be due to white spruce being sensitive to decreased levels moisture than the other species (AAFC, 2007). This being said, the carbon rates for the six species in the three different soil clusters were within 2-15% of one another (Figure 3.12).

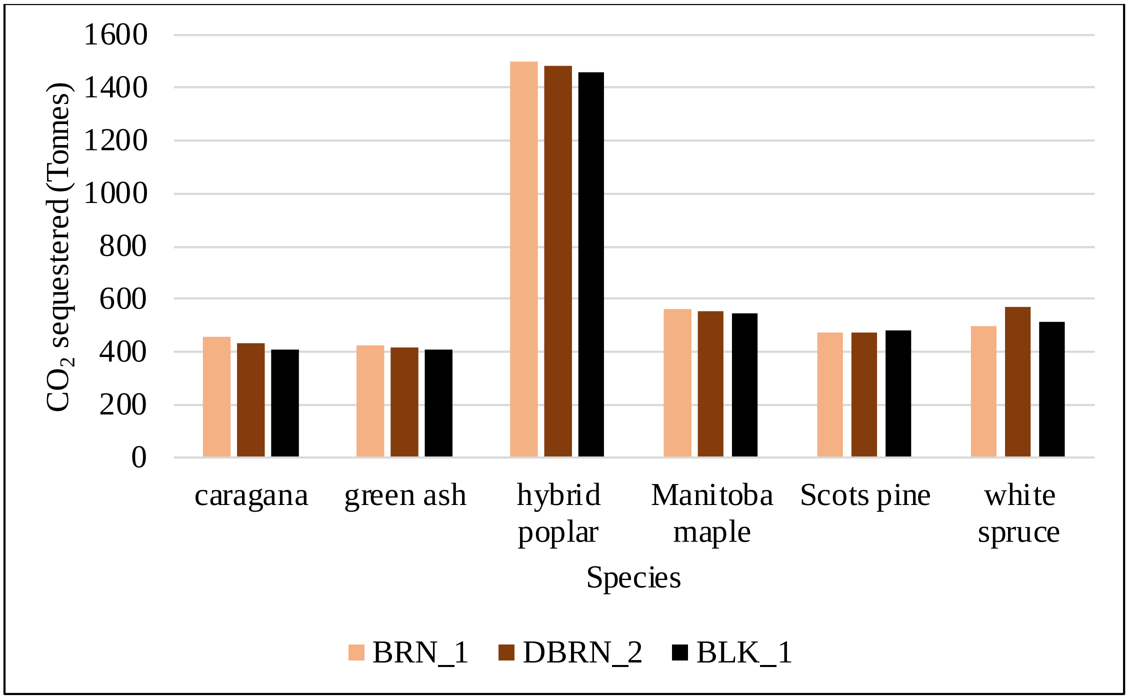

Figure 3.12 - Tonnes of CO_2 Sequestered by 60 Year Old Kilometre Long Shelterbelts for each Species by Soil Zone Cluster

All of the six shelterbelt species sequestered roughly the same amount of carbon regardless of soil zone cluster. Most shelterbelt species had slightly higher rates of biomass and carbon stocks in the Brown soil zone of the three soil zone clusters; however, the Brown soil zone cluster had fewer carbon stocks in the DOM, both prior to planting shelterbelts and following the removal of shelterbelt biomass. Of the tree soil cluster scenarios, hybrid poplar species had the greatest quantity of carbon sequestered by age 60. One of the reasons for hybrid poplar's carbon sequestration is their rapid rate of growth (Ball et al., n.d). However, it is important to note the lifespans of the different tree species such that hybrid poplars life span is 30 to 50 years (AAFC, 2015). Some hybrid poplars have lived much longer than this (~100+ years); however, some varieties of hybrid poplar mature around the 30-50 year mark, and carbon sequestration rates may decrease (AAFC, 2015). Therefore a trade-off of planting a fast growing, carbon sequestering-efficient shelterbelt of hybrid poplars is that they may not live as long, and therefore have a shorter term storage of said sequestered carbon, as other species. An example of a longer living tree is the Manitoba maple, which has a lifespan of 50+ years and has a moderate growth rate (AAFC, 2015). Manitoba maple is the second highest carbon sequestering shelterbelt tree species in the Black and Brown soil zone cluster scenarios, and the third highest in the Dark

Brown soil cluster scenario. The lifespan for caragana is similarly long at 50+ years and has a moderate growth rate, as does green ash (AAFC, 2015). White spruce has a slow growth rate and a life span of 50+ years (AAFC, 2015) and is the second highest sequestering species in the Dark Brown soil cluster scenario, and the third highest in the Black and Brown soil cluster scenarios. Scots pine has a moderate growth rate and has a lifespan of 50+ years (AAFC, 2015). The impact of lifespan on the sequestration abilities and storage longevity by different shelterbelt species was not a main priority in the reporting of net CO_2 sequestration values in this study as listed in study objectives. However, it is important to note as this is a pertinent area of research in carbon sequestration and specifically long-term storage by tree and shrub species.

The removal of the shelterbelt produces CO_2, as well as releases the stored carbon in the biomass of the removed trees and shrubs. The amount of CO_2 produced during the process of removal varies depending on the type of shelterbelt species to be removed and time required. It varies from 0.816 t CO_2 to 2.430 t CO_2. The amount of carbon sequestered over a 60 year period of a km long shelterbelt of each species puts into perspective the scale of the emissions caused by the planting and maintenance stages, which are small compared to carbon storage potential. In addition to this, the CO_2 that was stored as carbon in the biomass and DOM is both instantly and gradually released back into the atmosphere. The carbon loss from shelterbelt removal and burning in the Brown (BRN) soil cluster was immediately released. These values were: 310.75, 310.49, 1,204.83, 395.79, 407.59, and 425.97 t CO_2 for a km shelterbelt of caragana, green ash, hybrid poplar, Manitoba maple, Scots pine and white spruce, respectively.

For the Dark Brown (DBRN_2) soil zone scenario, the removal and burning of the 60 year old shelterbelt biomass released 307.23, 310.09, 1,204.12, 394.19, 411.07, and 508.81 t of CO_2 for caragana, green ash, hybrid poplar, Manitoba maple, Scots pine and white spruce, respectively. The values for biomass of the six species for both the Brown and Dark Brown soil zone clusters are very similar as they have similar growing conditions.

Following the removal of biomass, CO_2 continues to be emitted to the atmosphere in a more gradual pace from the remaining DOM through soil respiration. Prior to planting the shelterbelt trees, soil organic carbon already exist: however, the presence of the vegetation allows for an increase in this carbon storage. The presence of a 60 year old shelterbelt increases the DOM C levels by 26%, 29%, 33%, 40%, 16%, and 17% for caragana, green ash, hybrid poplar, Manitoba maple, Scots pine, and white spruce, respectively, in Dark Brown soil zone cluster. Overall, despite the shelterbelt species and the soil zone cluster, the carbon sequestration rate and potential of all planted shelterbelts surpasses the amount of emissions caused by the planting and maintenance of the seedlings.

To review, planting and maintenance will emit roughly 1.024 to 2.394 tonnes of CO_2 to the atmosphere. It is important to note that planting is a requirement and maintenance is highly recommended, depending on the area and conditions of shelterbelt establishment. All the species, excluding white spruce, will have negated the emissions caused by planting and maintenance and become a net carbon sink by the time they reach ten years of age. As white spruce is a slow growth tree, this species requires a slightly longer growing period (17-20 years) before they acquire enough biomass and become net carbon sinks. By the time, the one kilometre long shelterbelt is 20 years old, caragana will have sequestered roughly 53.91 tonnes of CO_2 in the BRN cluster, while the same species would sequester 48.63 and 42.53 t of CO_2 in the DBRN and BLK clusters. Different species can be planted based on the regional conditions and what species is best suited for them, and as well, they can be planted for different desired outcomes. As mentioned earlier this chapter, caragana and green ash are drought tolerant, and fast-growing trees. For this reason, they are commonly found as field shelterbelts and may be especially useful to plant in the arid regions of the Brown and Dark Brown soil zones. Hybrid poplar is another fast-growing tree species for landowners who want to yield high amounts of CO_2. A hybrid poplar shelterbelt in the BRN cluster yields roughly 138.21 t CO_2 by age 20, and upwards of 1,500.45 t CO_2 by 60; however, it is important to note the lifespan for this species is less than that of the other five species. Manitoba maple shows the quickest rate of sequestration in its early years, sequestering 31.54 t CO_2 by age 10 in the BRN soil cluster. The rate for Manitoba maple levels off to a more steady increase of CO_2 sequestration by age 20; however, this species has a longer life span, meaning it can be a carbon store for upwards up of 100 years.

3.6 Suggestions for Future Research

In order to minimize emissions in the planting phase, a landowner could consider planting by hand, rather than utilizing a mechanical tree planter. However, the level of emissions at this stage are relatively insignificant and in the presence of a tradeoff for more seedlings planted versus planting by hand, it may be more cost effective to use the tool of a tree planter. The maintenance of a shelterbelt can be critical for the survivability and overall health of the trees depending on the environmental conditions in which the shelterbelt is being planted. Specifically reference to considering irrigation, it is a high GHG emitting activities, as it accounted for 96% of the HFIT related emissions. In more moist regions or years that have increased precipitation, the application of irrigation may be significantly reduced, saving water use and therefore cutting emissions, potentially by 100%, or roughly 0.386 t CO_2. In addition to reduced irrigation, fertilizer may not be required if the soil is high in nutrients required for tree growth. This can be determined by conducting a soil test, which may lead to the need for fertilization. Tillage is often done for weed control and herbicide can be very crucial for regions where weed competition is high, specifically during the initial years of establishment. The application of these two maintenance components may be adjusted based on the presence of weeds, both annuals and perennials.

Regarding the removal of shelterbelts, avoiding the removal ensures highest levels of CO_2 sequestration and storage. If trees are damaged, dying or dead, the next best course of action is to replace the shelterbelt with new seedlings to ensure the continuation of carbon sequestration via biomass growth and in the DOM carbon stores. Replanting a shelterbelt following the removal will also change the carbon-cycling dynamic by discontinuing the slow-rate leaching of soil locked carbon to atmospheric CO_2 that occurs when carbon fixing vegetation is removed. Regardless of the removal of the shelterbelt biomass, the presence of a shelterbelt still added carbon to the soil as DOM carbon, which will remain a carbon sink for a number of decades following the removal.

3.7 Conclusion

In conclusion, each species sequesters CO_2 on a relatively consistent upward trend until the tree age of carbon saturation (i.e., reduced biomass growth) or once the tree lifespan is reached (60-100 years depending on species and lack of environmental/anthropogenic conditions causing an early death). Planting and maintenance was responsible for the emissions of 1.024 to 2.394 tonnes of CO_2. The gross rates of CO_2 sequestered by the shelterbelts of the six common shelterbelt species are comparable between the three soil zone clusters. All the species, excluding hybrid poplar, which sequesters significantly more, all sequester upwards of 400-500 t CO_2 by age 60. By age 60, in the BRN cluster, a shelterbelt of green ash will have sequestered roughly 424.71 t CO_2, the order following this is caragana < Scots pine < white spruce < and Manitoba maple, which sequesters 565.84 t CO_2. A hybrid poplar shelterbelt will sequester around 1500.49 t CO_2 by age 60 in the BRN cluster.

CHAPTER 4: CARBON LIFE CYCLE ASSESSMENT OF SHELTERBELTS IN SASKATCHEWAN – CARBON-BASED NET SOCIAL VALUE OF SHELTERBELTS

4.1 Introduction

The study on the complete carbon life cycle assessment for planted shelterbelts in Saskatchewan was divided into two phases: (1) Production of shelterbelt seedlings to be planted on the farms and transportation of seedlings from the point of production to the farms; and (2) Farm-level operation of shelterbelts (planting, maintenance, life-in-field, and removal). This Chapter focuses on the combined results for the full LCA, including all five life cycle phases, completing a net carbon LCA for the six shelterbelt trees and shrub species. Additionally, the potential economic worth of these shelterbelts, based on three pricing scenarios, is outlined. Finally, a variety of existing Canadian policies which provide financial incentive to adopt and retain environmental BMPs are listed.

4.2 Objective of Study

The objective of this study was to outline the complete Carbon-LCA of shelterbelt trees and shrubs. In this chapter these two parts – production of seedlings, and on farm level activities related to shelterbelts, are combined together to get a total net carbon sequestration potential of shelterbelts. This refers to net CO_2 rates by combining the amount of carbon produced during the life cycle stages and sequestered during the life of the tree. This chapter outlines emission as well as carbon sequestered. In addition to outlining these values, data on the current trends in pricing carbon is also provided. This may help the decision makers to place a monetary value on this important environmental service provided by the shelterbelts. This connection is relevant in the exploration and discussion of potential future related to policy development focused on climate change mitigation strategies.

4.3 Methodology

4.3.1 Goal, Scope, and Functional Unit

The goal of this study was to determine the net carbon balance by shelterbelt trees and shrubs by analyzing the different life cycle stages. The scope of this study included all the required inputs for the production of seedlings, as well as the most common regional methods of planting and maintaining shelterbelts.

4.3.2 System Boundary

The systems boundary outlines the scope in which the research was carried out. The system boundary is utilized to select relevant data for the study.

1. All the operations regarding the production and transportation of shelterbelt seedlings as well as all operations involving shelterbelts that occur at farm-level.
2. The inputs and equipment used for producing, transporting, plant, planting, maintenance, and removal of shelterbelts is included in this study; however, the raw materials and sourcing of said materials (e.g., production and transportation of chemicals used at the tree nursery and farms) were not included in the study, due to access of inventory information.
3. The CO_2 emissions for the production of seedlings is a broad all-encompassing value, regardless of species seedling. This was done for the sake of simplicity as well as due to lack of information regarding specific inputs to specific species seedlings.
4. The temporal boundary for the shelterbelt life cycle is 60 to 100 years, dependent on species. Data utilized in this study from research conducted by Amichev et al. (2016a) measured shelterbelts aged 5-100. From this research, the life span of White spruce shelterbelts varied from 6-76 years, Hybrid poplars from 13 to 55 years, Manitoba maple from 5-100 years, green ash from 5-80 years, Scots pine from 8-60 years, and caragana from 6-80 years (Amichev et al., 2016b). In this study, LCA scenarios for shelterbelts at different ages (10, 20, 30, etc.) were analyzed. The carbon sequestration of a km of each shelterbelt species was reported from age one to age 60 years. Similarly, the carbon stocks were estimated only to age 60 years for all six species. This was because there is no reliable reports of the carbon stocks following age 60 years.
5. A base value was utilized for the stages of preparing, planting, and maintenance. The maintenance focused on the use of herbicides, fertilizers, and irrigation and tillage

practices. The base level of maintenance was categorized by significant cultural practices used for shelterbelts, including irrigation use, tillage practices, and high application of chemicals. The stages of planting, maintenance and removal were analyzed through SimaPro to determine CO_2 production. The six species within three soil zones (Brown, Dark Brown, and Black) of the same mortality rate were also be analyzed to determine the difference in carbon sequestration by region and species.

6. Data collected for the LCA was entered into a LCA software program SimaPro to calculate the overall environmental loads associated with the production of shelterbelt seedlings. Proxy substances were used when sufficient information on a specific product did not exist. For example, if the data on a specific input (i.e., a certain brand of insecticide) and the exact type of insecticide does not exist in the databases within SimaPro, a proxy, general insecticide proxy was used.

4.3.3 Assumptions

Assumptions for an LCA are commonplace as it is difficult to establish the exact parameters and inputs for the scenario at hand. In the absence of data where knowledge gaps exist, assumptions are made. Assumptions in this research include:

1. A general production emissions value was assumed for all seedlings regardless of species.
2. Rather than creating scenarios for every different combination of herbicide, fertilizer, irrigation and tillage use, one level of shelterbelt maintenance was utilized. This assumption was based on recommendations found in literature (AAFC, 2010, Government of Alberta, 2007, and the Morton Arboretum, 2019) and survey of Saskatchewan agricultural producers conducted in 2017 and 2018. Recommended irrigation applications were followed over the first five years of establishment, along with herbicide application. The practice of tillage and fertilizer application were assumed as a one-time process during the initial year of planting.
3. Only the most commonly used chemical(s) and cultural practice(s) in the preparing/planting and maintenance stages of the LCA were used in the study. The less commonly used options were excluded.

4. All carbon values were expressed as carbon dioxide (CO_2) for reasons of comparability. Although carbon is stored in biomass and in soil as carbon, it was converted into CO_2 in this study.

4.3.4 Data Collection and Inventory Analysis

The data for the production of shelterbelt seedlings was sourced from a Saskatchewan tree nursery, Shand Greenhouse, which is located in Estevan, Saskatchewan. The Shand Greenhouse provides shelterbelt tree seedlings for purchase by landowners and free for those eligible through their shelterbelt program in the province of Saskatchewan. Data for this study were collected through personal communication (phone interviews and email correspondence) with the management of the SaskPower Shand Greenhouse (Bruce Hesselink, and Shelley Heidinger). Shand Greenhouse estimates that they produced approximately 500,000 plant seedlings on an annual basis (SaskPower, 2019). Data were also sourced from similarly scaled greenhouse operations, such as the University of Saskatchewan campus greenhouses, located in Saskatoon.

Information on equipment and materials used, and other required data for the analysis (e.g., hours to complete actions) were obtained from companies, such as Jays Transport, Beaver Plastics, and Shelterbelt Solutions. Data collected for this stage of the LCA were entered into a LCA software program SimaPro, which calculated the emissions from the overall life stages of production and transportation, as well form the individual inputs from each life cycle stages. Proxy substances, such as insecticides and certain machinery processes, were used when sufficient information on a specific product did not exist.

Data for the life cycle stages at the farm level were collected from face-to-face surveys using a structured questionnaire, which were administered over the summer field seasons of 2017 and 2018. The survey covered the overall farm operations (size, type), shelterbelt information (planting, maintenance, removal, as well as benefits and costs perceived by the landowner), and general information about the landowner. Relevant literature was also utilized to address certain data gaps, including recommended applications of herbicide, fertilizer and irrigation. The data on the rates of CO_2 sequestration by the six species in different soil zones was collected from AGGP (Agricultural Greenhouse Gases Program) Phase I studies (Amichev et al., 2016a & 2016b). Data on carbon pricing was sourced from government websites and literature regarding CO_2 reduction programs.

4.3.5 Economic Valuation Methods[7]

4.3.5.1 Production of Seedlings

The operational costs and inputs associated with the production of seedlings intended for shelterbelt establishment were based on the operations of Shand Greenhouse (detailed inventory of inputs with proxy data were presented in Appendix A). Heating of the greenhouse and associated buildings was done using waste heat generated from the neighboring coal-fired SaskPower power station, for which no records were kept. In order to determine this input cost, a greenhouse-heating calculator (ACF Inc., 2019) was utilized along with similar observations from other greenhouse operations (i.e., University of Saskatchewan campus greenhouses).

Within SimaPro, a number of methods are available to run data through depending on what environmental costs are to be analyzed. Different methods can be used for different environmental, social, and economic impacts. Selected LCI results is a method within SimaPro that generates focused values on a number of GHGs[8], including CO_2. Utilizing this method, the overall production of CO_2 can be determined within the entire process of production, as well as its breakdown by individual process inputs. For the purpose of this study, only CO_2 values outlined by SimaPro were reported; other environmental impacts (including other GHGs) were not covered.

4.3.5.2 Transportation of Seedlings

Shand Greenhouse employs a transport carrier (Jay's Transport) to complete some of their tree seedling deliveries. The seedlings are shipped to the three central hubs (Regina, Saskatoon, and Prince Albert). The transportation supplied by Jay's Transport is using a transport truck, weighing 7,711 kg (personal communication with Jays Managers). The boxes used for shipping weigh approximately 1 kg when full, and the transport truck accommodates approximately 200 #77 seedlings and 250 #112 seedlings. As the average shipment load includes 600-700 boxes, it would equate to a total seedling weight of 600-700 kg. In this analysis, the higher end of the general shipments, 700 boxes (700 kg), was used for the LCA. When entering transportation as a process in SimaPro, the unit for transportation is kg-km or tonne-km.

[7] This section is a summary of methodology already described in Chapters 2 and 3 for the sake of completeness.

[8] Other GHGs include: non-methane volatile organic compounds (NMVOC), CO_2, sulphur dioxide, nitrogen oxides, and particulates as well as land occupation, biochemical oxygen demand (BOD), and cadmium.

4.3.5.3 Planting Seedlings

There are two processes involved in the planting phase of the life cycle: tilling the land, and planting the seedlings. The CO_2 emissions attributable to individual inputs for both life stages are outlined in Table B.1. A base input scenario for tilling the land was used for the three different tree variety categories: shrub, coniferous, and deciduous. This scenario involved tilling the area of the functional unit. The process of planting tree seedlings was based on species type due to recommended spacing. A base value of planting a seedling is utilized for all seedlings in this research, regardless of species. The length is the functional unit of one km (1,000 m) and the width of 1 metre representing an area of tillage of 1000 m^2.

The number of trees that can be planted in a kilometre linear row is based on the tree species and their recommended spacing. For reference, caragana is a shrub species, hybrid poplar, Manitoba maple, and green ash are deciduous species, and white spruce and Scots pine are coniferous species. The recommended minimal spacing for shrubs is 1 metre, for deciduous and coniferous trees is 2.5 m and 3.6 m, respectively (AAFC, 2010). Based on these recommended spacing, the maximum number of trees planted in a km long shelterbelt are as follows: 1,000 shrubs, 400 deciduous trees, and ~277 coniferous trees. For spacing between adjacent rows, it is recommended that a minimum distance of 5 m be left between adjacent rows of the same tree variety (deciduous or coniferous). When deciduous rows and coniferous rows are adjacent, the recommended spacing is 6 m (AAFC, 2012).

4.3.5.4 Maintenance of Shelterbelt

Shelterbelt maintenance included application of herbicides, fertilizers, irrigation and tilling of the land prior to planting and any weed management surrounding the belt (HFIT). There is one maintenance level used for the Carbon-LCA, details for which have been presented in Table B.1.

4.3.5.5 Life in Field

Data on the carbon stock value estimations of the six shelterbelt species were obtained from studies completed under the auspices of the first phase of the Agricultural Greenhouse Gases Program (AGGP I) by Amichev et al. (2016a and 2016b). As noted earlier, the data collected for the carbon stocks of the six shelterbelt tree and shrub species were recorded until the trees reach an age of 60 years since there were no reliable data on carbon sequestration rates for trees older than 60 years. Carbon sequestration is dependent on a number of factors, including average life span of the tree (AAFC, 2018).

For this study, three representative soil zone clusters were selected for estimating level of sequestered carbon representing Brown (BRN), Dark Brown (DBRN), and Black (BLK) soil zones. As the data on carbon stocks were recorded by soil clusters, a distinction between carbon sequestrations for soil zones can be made. It is important to note that the soil has carbon stored prior to planting of the shelterbelts. The carbon locked in the soil and root systems is referred to as DOM (dead organic matter). The BLK soil cluster shows the highest amount of preexisting carbon in the soil prior to planting shelterbelts. This is characteristic of the Black soil zone, as it tends to be moist and rich in carbon and other nutrients compared to the Brown and Dark Brown soil zones, which can be nutrient-deprived and arid.

Over time the shelterbelt species in the BRN soil cluster yield the largest gains in biomass, and therefore higher CO_2 sequestration rates by their maturity at age of 60 years. The Brown soil zone is characterized by its more arid conditions and it is very common for shelterbelt adoption to protect against soil erosion and increase moisture retention. In contrast the DBRN soil cluster had the second most biomass addition of the three soil zones. The majority of shelterbelts were found in this soil zone in Saskatchewan. The Black soil zone showed the least biomass additions of the three soil zone clusters selected for this research. However, BLK reported the highest overall TEC CO_2 values due to its increased amount of DOM carbon. Carbon and nutrient-dense soils are typical of the Black soil zone so this discovery is in accordance with that characteristic. The full tables detailing the amount of CO_2 in tonnes sequestered by a km long shelterbelt of each species in increments of five years until age 60 in each soil zone cluster is outlined in Appendix C.1 through C.3.

The rate of sequestration from the growth of the tree and shrubs begins as a negative value for the initial years after being planted (i.e., it is a carbon source rather than a carbon sink). The reason for this is that there are microbes that are continuously decomposing carbon within the soil, which creates a release of CO_2 from the soil to the atmosphere. This occurs naturally in soil, specifically when there is no vegetation fixing more carbon into the soil. A slight but steady decrease of CO_2 from soil to atmosphere is observed following the removal of shelterbelts as well, which is discussed below. The shelterbelt requires a few years to establish its roots system and aboveground biomass (branches, crown, and foliage). For this reason, a shelterbelt (of any species) is not immediately a carbon sink. Excluding the addition of CO_2 from the life stages, a shelterbelt of caragana becomes a carbon sink (i.e., positive CO_2 value sequestered) by the age four.

4.3.5.6 Removal of Shelterbelt

Shelterbelt Solutions, a Shelterbelt and Tree Row Removal company based out of North Dakota, provided information on their shelterbelt removal process using skid loaders and wheel loaders. They typically construct their own attachment for the removal, and utilize grapple attachment for the cleanup. The time required for removal varies dependent on species, whether the trees are alive or dead, and length of shelterbelt/number of trees. Estimates provided by Shelterbelt Solutions (2019) included machine hours for the removal of a half mile (~805 m) of different species: 30-40 hours of machine use to remove green ash trees; 20 hours to remove caragana; 40 hours to remove pine/spruce; 40-50 hours for smaller sized hybrid poplar; and 100-150 hours for larger hybrid poplars (Shelterbelt Solutions, 2019). As the specifics of the equipment for removal are unknown, a proxy was utilized for this LCA. The inputs on removal are displayed in Table presented in Appendix B (Table B.2). In addition to CO_2 being released form the process of removing shelterbelts, CO_2 is also lost due the incineration of the removed woody biomass post removal. Burning shelterbelts is a common practice in the prairie region.

4.4 Results

The results for the CO_2 emissions created at each life cycle stage were conducted utilizing the inputs for each life stage and entering them into the LCA software program SimaPro. These input values were then analyzed using a method that is part of the SimaPro package, called LCI Select, which is used to isolate the CO_2 emissions from each life cycle stage.

4.4.1 Overview of LCA Stages

In this study, the LCA for a shelterbelt included five stages: (1) production of seedlings, (2) transportation of seedlings, (3) planting and maintenance of seedlings, (4) life in field, and (5) eventual removal of the shelterbelt. The results from the LCA analysis for each of these stages are presented in this section.

4.4.1.1 Production

In Chapter 2, the production and transportation of shelterbelt seedlings was analyzed to estimate the amount of CO_2 produced. The total CO_2 production for one year of seedling production was calculated to be 1,100 t. As one year of production yields approximately 500,000 seedlings, the emissions attributable to one seedling is 1,100/500,000 = 0.002 t CO_2. Therefore, the production emissions for the number of seedling required for one km of shelterbelt or 277 coniferous seedlings, 400 deciduous seedlings and 1,000 shrub seedlings was 0.61 t CO_2, 0.88 t CO_2, and 2.20 t CO_2, respectively.

4.4.1.2 Transportation

The transportation from the Estevan, SK (where Shand Greenhouse is located) to the three different transportation hubs: Regina, Saskatoon, and Prince Albert, SK had CO_2 emissions of 6.08, 14.10, and 17.20 tonnes, respectively.

4.4.1.3 Planting

The phase of planting consists of tilling the land prior to planting, followed by the process of planting itself. As in the scenario, area of 1,000 m^2 (one km x 1 m) was assumed, the process of tilling remains the same for all three planting scenarios. Therefore, the value for the process of planting seedlings is depending on type of shelterbelt planted: coniferous, deciduous, or shrub.

4.4.1.4 Maintenance

The maintenance phase included the HFIT (Herbicide, Fertilizer, Irrigation and Tillage application) components.

4.4.1.5 Removal

Removal of shelterbelt was conducted by utilizing a skid-steer with attachment and excavator to uproot underground biomass. The CO_2 emissions attributable to the machinery used for the removal of a one kilometre long shelterbelt for the three different shelterbelt categories: shrub, coniferous and smaller sized deciduous, and larger sized deciduous (large hybrid poplars).

4.4.2 Net CO_2 Sequestered by Shelterbelt Trees and Shrubs

In order to determine the net carbon sequestered and stored by shelterbelt tree and shrub species, all the life cycle stages need to be accounted for. An overview of CO_2 emissions in tonnes from each life cycle for a shelterbelt of 1000 seedlings is outlined in Table 4.1. For example, assuming a scenario of a delivery to Saskatoon, the CO_2 emissions from the production and transportation for 277 seedlings (shelterbelt of coniferous trees) would be 0.03 tonnes (transportation) + 0.61 tonnes (production) = 0.64 tonnes CO_2. The emissions for a scenario of

400 (shelterbelt of deciduous trees) and 1,000 (shelterbelt of shrubs) would equate 0.92 tonnes and 2.3 tonnes of CO_2, respectively. The planting phase adds a CO_2 emission of 0.53 tonnes to plant a coniferous shelterbelt (277 trees). Planting a coniferous shelterbelt (400 trees) and shrub (1,000) shelterbelt is responsible for 0.76 and 1.90 tonnes CO_2. The CO_2 produced from maintenance is 0.49 tonnes. Therefore the total negative CO_2 value (i.e., quantity of emissions) for the all the LCA stages (excluding removal at this point) – i.e., production, transportation, planting and maintenance, would be 1.66, 2.18 and 4.68 tonnes CO_2 for 277, 400, and 1,000 seedlings, respectively.

Table 4.1 - CO_2 Emissions in Tonnes by Life Cycle Phase for the Production, Transportation, Planting, Maintenance and Removal of 1000 Seedlings

Life Phase	**Tonnes CO_2**
Production	2.20
Transportation	0.09
Planting	1.90
Maintenance	0.49
Removal	1.12
Total	5.80

Table 4.1 shows the emissions caused by the different life cycle stages, specifically for a scenario of 1,000 seedlings; the amount commonly used in reference in this research for a kilometre long shelterbelt of shrub (caragana) species.

Including these values of CO_2 emissions that occurred in the initial phases to establish a shelterbelt (production, transportation, planting, and maintenance), the net CO_2 value for the sequestration rates were slightly decreased. Table 4.2 denotes the net CO_2 values for each of the species regarding a 60 year old kilometre long shelterbelt in the three soil zone clusters. Note that although the emissions for removing a km long shelterbelt are included in the life phase emissions (Table 4.2), they are calculated into the net CO_2 value as this process occurs following this sequestration.

Table 4.2 - Net CO_2 in Tonnes for a Kilometre Long 60-Year Old Shelterbelt by Species in the Three Soil Zone Clusters

Soil Cluster	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
BRN	450.20	423.05	1481.14	564.16	474.97	493.61
D_BRN	432.24	414.04	1481.14	554.35	468.11	569.83
BLK	406.03	405.85	1481.14	543.14	481.49	508.40

Taking into account the emissions caused by the life cycle stages, net the CO_2 sequestered by the different shelterbelt species is only slightly decreased from the gross value of CO_2 sequestration. For a coniferous shelterbelt 1.66 t CO_2 is added for a shelterbelt of coniferous trees (Scots pine and white spruce), 2.18 t CO_2 is added for a shelterbelt of deciduous trees (green ash, hybrid poplar, and Manitoba maple), and 4.68 t CO_2 is added for a shelterbelt of shrub species (caragana). It is important to note that these values were estimated assuming the respective type of shelterbelt is utilizing the maximum trees allotted within spacing recommendations.

All species in the BRN soil cluster became net carbon sinks at the age of five, save for green ash. Netting out the emissions caused by the production, transportation, planting and maintenance phases only shifts this date by a few years. White spruce, as shown in Figure 4.8, has the slowest rate of sequestration CO_2 during its early years in life and does not become a net carbon sink until roughly year 16; however, it shows a significant upwards trend during the period following. By age 20, a white spruce shelterbelt in the BRN will have sequestered a net sink of 15.03 t CO_2, including emissions from life cycle phases.

4.4.3 Price of Shelterbelt Seedlings

There are many public programs that have existed in the prairie regions of Canada that have served as a shelterbelt seedling distribution center. An important program that previously existed and served Saskatchewan was the Prairie Farm Rehabilitation Center (PFRA), which operated out of Indian Head, Saskatchewan. This program supplied landowners with hundreds to thousands of tree seedlings for shelterbelt establishment, free of cost.

Establishing a number of shelterbelts on one's land can be costly if free seedlings through a shelterbelt program are not available. As mentioned previously, Shand Greenhouse offers free seedlings for those who are eligible. However, the price breakdown of seedlings in various locations was provided via Shand contact (Bruce Hesselink, 2018). The list below shows the price ranges for various seedlings:

1. *White spruce: ($2.80/seedling)*
2. *Scots pine ($2.60 - $2.95/ seedling)*
3. *Manitoba maple ($2.80 - $3.45/seedling)*
4. *Green ash ($2.80 - $3.45/ seedling)*
5. *Hybrid poplar ($1.75 - $5.37/ seedling)*
6. *Caragana ($2.80 - $3.45/ seedling)*

For example, for a full kilometre shelterbelt of coniferous seedlings (roughly 277 seedling based on spacing recommendations by the AAFC, 2010), the cost to purchase those seedling can be $775.6 for white spruce and $720.20-817.15 for Scots pine. For a shelterbelt of deciduous trees (roughly 400 seedlings), the cost to purchase can be $1,120-1,380 for Manitoba maple or green ash, and $700-2,148 for hybrid poplars.

The importance of outlining the cost of shelterbelt adoption, where free seedling distribution programs do not exist/are not as large-scale, is the impact this has on the likelihood of landowners choosing this as a land management practice. Most landowners with shelterbelts have more than one row of trees. Many landowners will have several shelterbelt rows surrounding their house and farmyard as well as multiple more rows in their fields. Considering the potential cost of $1,120 or more for a single kilometre long shelterbelt can be a major deterrent for adoption of shelterbelts by landowners.

4.4.4 Carbon Pricing

Carbon pricing is a policy approach to introduce a cost to the emissions of CO_2 that are created by individuals, households, businesses and industry. Often expressed as a price point by tonne of CO_2 emissions, carbon pricing is utilized to introduce a monetary incentive to reduce emissions. The Canadian government outlined its carbon pricing policy beginning with $10/tonne CO_2e in 2018. The price of carbon will increase by $10/t CO_2e annually until reaching $50/t CO_2e in 2022 (Government of Canada, 2019b). In order to determine an associated price for the adoption and retention of shelterbelts, the annual amount that is sequestered needs to be outlined. The amount of CO_2 that a shelterbelt sequesters annually steadily increases as it grows, with some dips.

4.4.5 Value of Sequestered Carbon

Given the rate at which CO_2 is sequestered by a shelterbelt annually and assuming a price of a tonne of CO_2 for different years, (such as \$20, \$30, \$40, and \$50 for the year 2019, 2020, 2021, and 2022+, and beyond, respectively), the dollar value of the CO_2 sequestered annually can be determined. For example, a 10-year-old 1 km length caragana shelterbelt over 50 years (until the shelterbelt reaches age 60) results in CO_2 being sequestered based on current Canadian carbon tax pricing is displayed in Figure 4.1, as well two other pricing scenarios. Figure 4.1 denotes the annual worth price points of the shelterbelt based on its CO_2 sequestration amount. Note: this figure shows the annual CO_2 sequestered and respective monetary value based on three pricing scenarios; it does not display a cumulative value of CO_2 sequestered over the life of the shelterbelt.

The low pricing scenario assumes that one tonne of CO_2 remains at \$10, which is the carbon tax price point of a number of countries such as Argentina (World Bank Group, 2019). The high price scenario follows the guidelines of countries such as Sweden and assumes a carbon price of \$171/t CO_2 (World Bank Group, 2019). These figures show the potential social worth of CO_2 sequestered depending on different carbon pricing scenarios. This information is important for future decision-making regarding shelterbelt adoption and retention. In order to properly determine the financial benefits associated with choosing sustainable management practices such as shelterbelt adoption and retention, the worth of the CO_2 sequestered itself needs to be highlighted. The monetary value of CO_2 sequestered is based on the set price of CO_2 emissions in these three scenarios. For example, based on Canadian carbon tax pricing, the CO_2 sequestered the 30th year for the caragana shelterbelt, in 2040, the shelterbelt could be worth of \$421.65.

These values assume that the shelterbelt is healthy and thriving and therefore sequestering this amount of CO_2. Many variables could affect the amount of CO_2 sequestered, and therefore the associated worth of said carbon. In figure 4.1 it is assumed that the shelterbelt is 10 years old in 2020, therefore the price of \$30/t CO_2 carbon tax would apply, increasing by \$10/t CO_2 and leveling off in 2022 at \$50/t CO_2 onwards (age 12+ for the shelterbelt) (Figure 4.1). In addition to this, two other scenarios of carbon pricing are demonstrated, a low and a high carbon pricing example. In figure 4.1, the price in \$CAD is denoted on the left y axis. The annual CO_2 sequestered is accounted for on the right axis.

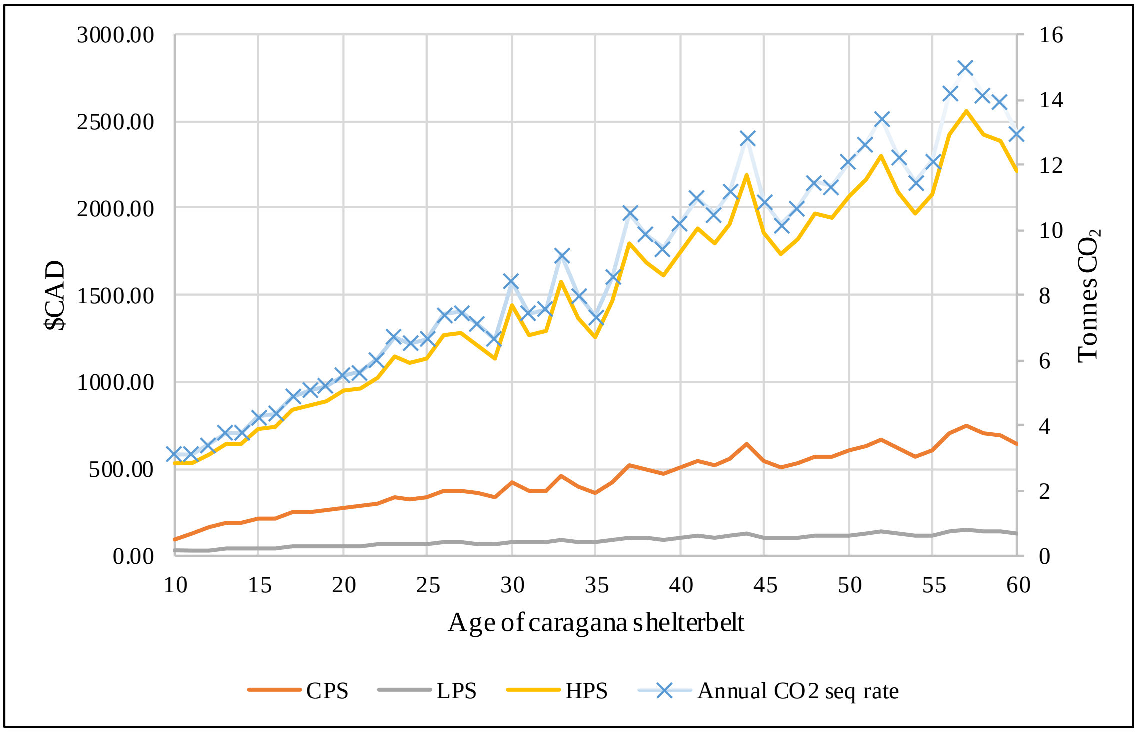

Figure 4.1 - Social Worth of CO_2 Sequestration at Three Price Point Scenarios based on Carbon Pricing in Canada (CPS), Argentina (LPS) and Sweden (HPS) in 2020 for a Shelterbelt of Caragana in the BRN Soil Cluster

The annual CO_2 sequestration rate for a one kilometre long shelterbelt of Manitoba maple from age 10 to age 60 is also evaluated for the values provided by carbon payments (Figure 4.2). By age 10, this shelterbelt has already sequestered a total of 31.54 t CO_2, whereas a shelterbelt of caragana would have sequestered 10.48 t CO_2. However, caragana shows a continuation of sequestration rates following age 10, whereas for Manitoba maple the sequestration rate tends to increase at a lower rate, with spikes and drops in sequestration. Both shelterbelts provide the opportunity for large payments should such a program exist in Canada. For Manitoba maple at age 30 (in 2040), the annual worth of this shelterbelt was estimated at \$573.85 per kilometre (cumulative of annual sequestration by age 30 multiplied by \$CAD per tonne of CO_2).

In contrast to the growth, and sequestration profiles, of caragana and Manitoba maple, white spruce is a slow-growing species, and therefore it becomes a net carbon sink later than any of the other shelterbelt shrub and tree species evaluated (Figure 4.3).

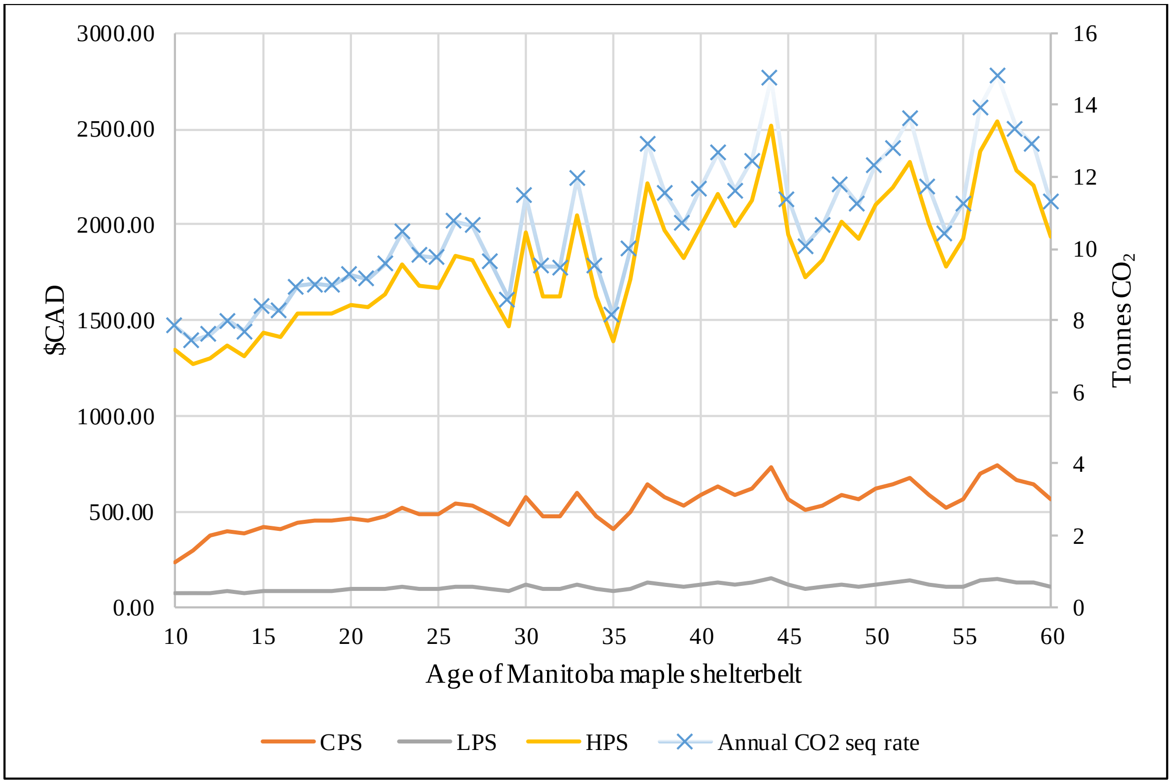

Figure 4.2 - Social Worth of CO_2 Sequestration at Three Price Point Scenarios based on Carbon Pricing in Canada (CPS), Argentina (LPS) and Sweden (HPS) in 2020 for a Shelterbelt of Manitoba maple in the BRN Soil Cluster

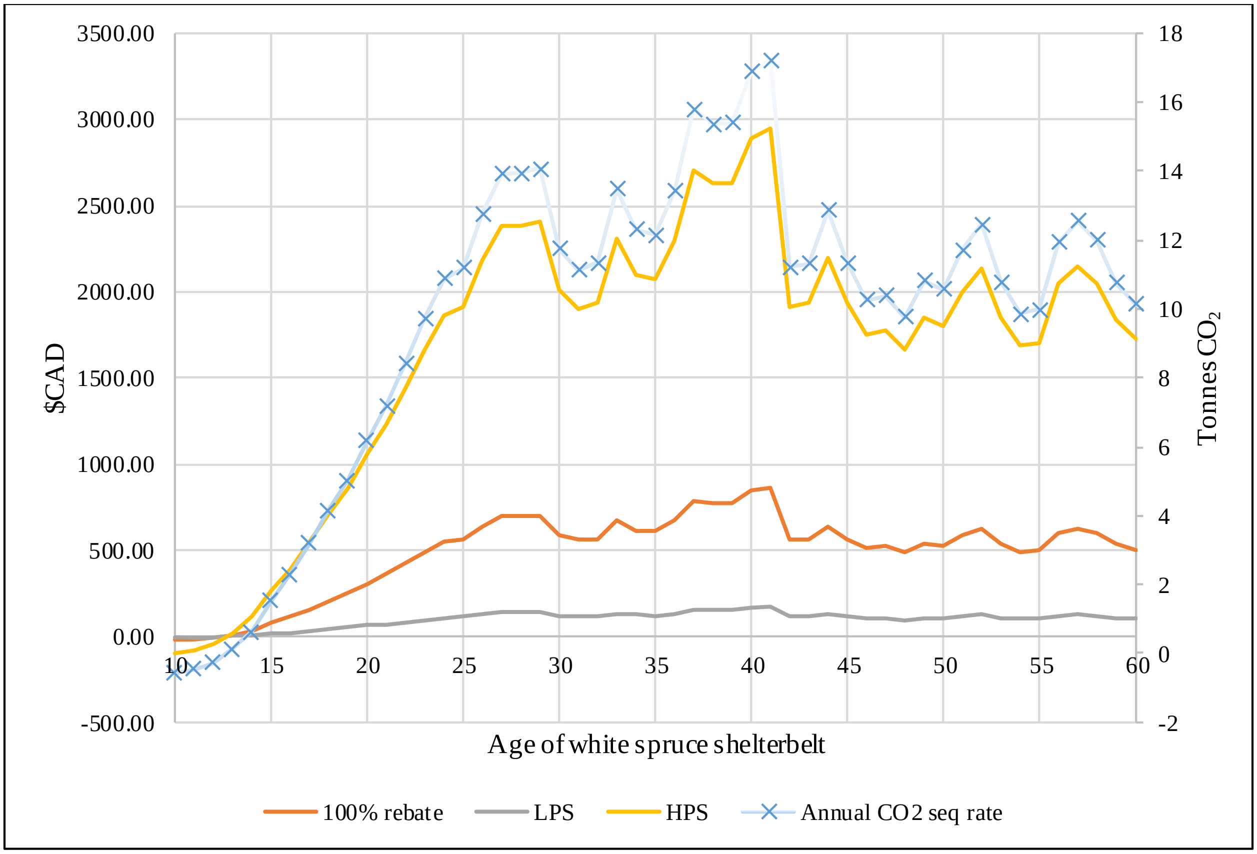

Figure 4.3 - Social Worth of CO_2 Sequestration at Three Price Point Scenarios based on Carbon Pricing in Canada (CPS), Argentina (LPS) and Sweden (HPS) in 2020 for a Shelterbelt of White spruce in the BRN Soil cluster

White spruce follows a steady upwards climb of sequestration rates until following age 40, where its sequestration rate drops slightly and then levels off. This may be due to a decrease in biomass growth in its later years of life. Following the peak of carbon sequestration, an amount upwards of $487.58 worth of CO_2 could be sequestered annually, should any payment resembling these values come to fruition in future policymaking. A shelterbelt of Manitoba maple, assuming it is healthy and sequestering to its highest capability, can sequester 128.29 t CO_2 by age 30 and 493.61 t CO_2 by age 60.

4.5 Discussion

4.5.1 Net CO_2 Sequestered by Shelterbelts

The difference in gross versus net CO_2 that is sequestered by all six shelterbelt species in each of the three soil zone clusters is not large. The added CO_2 emissions from the life cycle phases of production, transportation, planting and maintenance is minor in comparison to ability to sequester CO_2 within the first ten years of planting a shelterbelt (excluding white spruce, which requires 18 years before becoming a positive CO_2 sink).

4.5.2 Economics of Shelterbelts

4.5.2.1 Benefits of Shelterbelts

One goal of outlining the net CO_2 values for the six common shelterbelt species was to outline the worth of CO_2 sequestration of shelterbelts in the adoption and retention of shelterbelts on one's land. Shelterbelts are beneficial for a number of environmental and socio-economic reasons[9]. However, shelterbelts are not without their associated costs. The PFRA Shelterbelt Centre previously operated out of Indian Head, Saskatchewan and distributed seedlings, free of charge, to landowners in Saskatchewan for the majority of the 20th century (Rempel, 2017). In the absence of this type of large-scale functioning shelterbelt tree distribution program, some landowners may find that purchasing large numbers of tree and shrub seedlings to be a monetary disincentive to shelterbelt establishment. However, based on the predicted values of CO_2 sequestered by a km shelterbelt of Manitoba maple, the start-up costs of buying seedlings of \$1,120- \$1,380 would be paid back based on the value of CO_2 sequestration within the first 10 years which would equal an accumulation of \$1,595.61 based on current Canadian federal carbon pricing values.

Another concern with shelterbelts is their size and placement along crop fields in the era of increasingly large farm equipment. This has become a common reason for removing field shelterbelts by farmers as they have become inconvenient to navigate around during seeding, spraying, and harvest with large sized equipment, as well as crop land loss to shelterbelts. Another reason for removal included the perceived lack of necessity, as shelterbelts were widely planted to reduce soil erosion and as many farmers have adopted a no-till strategy to annual crop production, soil erosion concerns have lessened significantly (Rempel, 2017).

As mentioned previously, management practices in which carbon sequestration or storage occurs (i.e., the adoption and retention of shelterbelts) has not been explored in policy. Specifically in light of a federal carbon tax being introduced as a climate change mitigation

[9] Shelterbelts can provide several environmental goods and services, such as microclimate modification, pollination, habitat benefits, among others. However, estimation of these benefits was considered beyond the scope of this study.

strategy, the importance of exploring other policies and programs with the same goal should be explored.

4.5.2.2 Shelterbelts and the Carbon Tax

In 2016, the Federal Government of Canada introduced an initiative for a nation-wide carbon tax or carbon cap and trade equivalent. Each province was given until 2018 to put in place an appropriate carbon pricing strategy (Government of Canada, 2019b). The carbon pricing plan puts a dollar amount on CO_2 emissions. For 2019, this value is set at \$20/tCO_2e, to rise to \$50/tCO_2e in 2022 (Government of Canada, 2019). Currently, policy regarding carbon sequestration efforts in light of a federal carbon tax have not been outlined. Farm fuel is exempt from the carbon tax, however, indirect costs will be increase for farmers (APAS, 2019). It is estimated that the carbon tax will cost farmers in Saskatchewan roughly \$1.99/acre in 2019 and \$3.85/acre in 2022 (APAS, 2019) considering grain drying, rail, truck, heating, and electricity. Fertilizer was not included in these calculations, due to the price increase being decided by fertilizer producers rather than landowners.

4.5.2.3 Existing Climate Mitigation Policy in Canada

There are a number of programs which already exist in Canada that strive to encourage landowners to implement a management plan to sequester and store carbon. Examples of said programs are overviewed below.

A management payment program in Saskatchewan that offer funding to landowners who implement BMPs, specifically in the areas of water, climate change and biodiversity, the Farm Stewardship Program (FSP), has focused on a number of desired environmental outcomes, one being the reduction in greenhouse gas emissions. Previously through the Growing Forward 2 initiative, landowners could receive a rebate of \$1,200 per mile (804 m) with a maximum of \$5,000 for planting shelterbelts (Growing Forward 2, 2016).

In British Colombia, the 2018-2019 BMP Program outlined *Shelterbelt Establishment* as a BMP under the *Landscape* category. The individual cost sharing is 60% and funding cap is \$15,000 (ARDCORP, 2018).). While in Ontario, there is a Managed Forest Tax Incentive Program (MFTIP), which offers a reduction in property taxes to landowners of forested land. Under the MFTIP, landowners are taxed 25% of the residential land tax rate. Those eligible for this BMP must have a minimum of 9.88 acres of forested land; meet the minimum number of trees required per acre; prepare and have approved a 10 year Managed Forest Plan; and make a commitment to practice good land stewardship (Ontario Ministry of Natural Resources and Forestry, 2019).

These BMPs within the different provinces are outlined to note the existence of government programs which encourage the adoption of sustainable management on one's land. The data from this research on CO_2 sequestration by six common shelterbelt tree and shrub species can be utilized to help model a BMP in which landowners receive an incentive to adopt and maintain shelterbelts on their land due to their ecological service of carbon sequestration. These policy examples encourage GHG mitigation, and therefore are important in the context of climate change. Policy is needed to the role played by shelterbelts in GHG mitigation through tree and soil carbon sequestration.

4.6 Future Research

Research on the carbon sequestration by shelterbelts related to their lifespans is a topic that can be further researched as it may impact the decision-making process for selection of species on one's land. More research on the potential for BMPs related to shelterbelt adoption and retention needs to be explored and discussed as a tool for climate change mitigation. As it becomes more common to remove shelterbelts due to increasing farm equipment size and decreased concerns regarding soil erosion, additional incentives may be required to keep shelterbelts and therefore carbon stores up in the province of Saskatchewan. The exploration of existing programs which reward landowners in some capacity, whether that be fund-sharing, reductions/rebates in taxes or other incentives, are steps in the right direction. More effort is needed to develop policies that would entice producers to maintain existing shelterbelts, and plant new ones.

4.7 Conclusion

In conclusion, the emissions created by the life cycle phases of production, transportation, planting and maintenance are negligible compared to the scale of the CO_2 sequestered by the shelterbelt species evaluated. For example, if even a half km long shelterbelt of caragana shrub species were planted, the CO_2 that is sequestered in the BRN soil cluster by age 20 is still 12.07 t CO_2, which rectifies the emissions of 2.34 t CO_2 required to enable the existence and survivability of the seedlings. Hybrid poplar sequesters the most CO_2 by far; however, other species may serve as longer-term storage due to increased life spans. The removal of shelterbelts as a process in addition to the burning of biomass of removed shelterbelts will release a significant portion of CO_2 back into the atmosphere. Roughly half of the TEC CO_2 remains in the soil, however there is slow release of soil locked carbon to the atmosphere in the absence of a new shelterbelt being planted.

There is significant potential for the creation of government BMPs to reduce the emissions from rural landowners via the adoption and retention of shelterbelts, as well as reward landowners through rebates for making sustainable management choices.

References

ACF Inc. 2019. Greenhouse Heater Calculator. Aaron's Creek Farms. Retrieved from http://www.littlegreenhouse.com/heat-calc.shtml#cost.

Agricultural Producers Association of Saskatchewan (APAS). 2019. Backgrounder: Preliminary Costs of the Federal Caron Backstop on Saskatchewan Agriculture.

Agriculture and Agri-Food Canada (AAFC). 2007. Field Shelterbelts for Soil Conservation. Agri-Facts. Retrieved from https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex2073/$file/277_20-3.pdf?

Agriculture and Agri- Food Canada (AAFC). 2010. AAFC-AESB Prairie Shelterbelt Program Frequently Asked Questions. AESB Agroforestry Development Centre.

Agriculture and Agri-Food Canada (AAFC). 2012. Spacing recommendations. Government of Canada. Retrieved September 30 2019 at http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/agroforestry/shelterbelt-planning-and-establishment/spacing-recommendations/?id=1344895588418.

Agriculture and Agri-Food Canada (AAFC). 2015. Planting new trees and shrubs. Retrieved June 2018 https://www5.agr.gc.ca/eng/science-and-innovation/agricultural-practices/agroforestry/growth-and-maintenance-of-trees/planting-new-trees-and-shrubs/?id=1346110148472.

Agriculture and Agri- Food Canada (AAFC). 2018. Selecting trees and shrub species. Government of Canada. Retrieved on July 18 2019 at http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/agroforestry/shelterbelt-planning-and-establishment/selecting-trees-and-shrubs-species/?id=1344895876238.

Aldentun, Y. 2002. Life cycle inventory of forest seedling production—from seed to regeneration site. Journal of Clean Production 10(1):47–55.

Amadi, C. C. 2016. Dynamics of carbon dioxide, methane and nitrous oxide fluxes in planted shelterbelts and adjacent cropped fields. Ph.D. dissertation, University of Saskatchewan, Canada.

Amadi, C. C., Van Rees, K. C. J., and Farrell, R. E. 2016. Soil – atmosphere exchange of carbon dioxide, methane and nitrous oxide in shelterbelts compared with adjacent cropped fields. Agriculture, Ecosystem and Environment 223:123-134.

American Nursery and Landscape Association. 2004. American standards for nursery stock. ANSI Z60.1–2004. ISBN 1-890148-06-7. 129 p. American Nursery & Landscape Association; 1000 Vermont Avenue, NW, Suite 300; Washington, DC 20005 www.anla.org

Amichev, B., Kurz, W., Smyth, C., and Van Rees, K. 2012. The carbon implications of large-scale afforestation of agriculturally marginal land with short-rotation willow in Saskatchewan. Global Change Biology 4(1):70-87.

Amichev, B., Bentham, M., Kulshreshtha, S., Laroque, C., Piwowar, J., and Van Rees, K. 2017. Carbon sequestration and growth of six common tree and shrub shelterbelts in Saskatchewan, Canada. Canadian Journal of Soil Science 97:368 – 381.

Amichev, B. Y., Bentham, M.J., Werner. A.K., Laroque, C., Kulshreshtha, S., Piwowar, J., and Van Rees, K. 2016. Carbon sequestration by white spruce shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 model simulations. Ecological Modelling 325:35 – 46.

Amichev, B. Y., Bentham, M.J., Cerkowniak, D., Kort, J., Kulshreshtha, S., Laroque, C., Piwowar, J., and Van Rees, K. 2014. Mapping and quantification of planted tree and shrub shelterbelts in Saskatchewan, Canada. Agroforestry System 89:49 – 65.

Amichev, B.Y., Bentham, M.J., Cerkowniak, D., Kort, J., Kulshreshtha, S., Laroque, C.P., Piwowar, J.M., and Van Rees, K.C.J. 2015. Mapping and quantification of planted tree and shrub shelterbelts in Saskatchewan, Canada. Agroforestry Systems 89:49-65. doi:10.1007/s10457-014-9741-2.

Amichev, B.Y., Bentham, M.J., Kurz, W.A., Laroque, C.P., Kulshreshtha, S., Piwowar, J.M., and Van Rees, K.C.J. 2016a. Carbon sequestration by white shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 model simulations. Ecological Modeling 325:35—46.

Amichev, B.Y., M.J. Bentham, S. Kulshreshtha, W.A. Kurz, C.P. Laroque, J.M. Piwowar, and K.C.J. Van Rees. 2016b. Carbon sequestration by planted shelterbelts in Saskatchewan: 3PG and CBM-CFS3 model simulations. Ecological Modelling 325:35-46.

ARDCORP — BC Agricultural Research & Development Corporation. 2018. Canadian Agricultural Partnership – Beneficial Management Practices 2018/19. Environmental Farm Plan. Retrieved Nov 10 2019 at http://ardcorp.ca/wp-content/uploads/2018/06/2018-19-BMP-List-Version-3.0-June-21-FINAL.pdf.

Ares, E., and Delebarre, J. 2016. Briefing Paper - The Carbon Price Floor. House of Commons Library. Retrieved June 2017 from researchbriefings.files.parliament.uk/documents/SN05927/SN05927.pdf.

Ball, J., Del Lungo, A., and Carle, J. n.d. Contribution of poplars and willows to sustainable forestry and rural development. Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/3/a0026e/a0026e02.htm.

Balmes, J. R. 2014. California's Cap-and-Trade Program. Global Climate Change and Public Health 7, 383-391. DOI: 10.1007/978- 1 -4614-8417-2_22.

Bond-Lamberty, B., Wang, C., Gower, S. T. (2004), A global relationship between the heterotrophic and autotrophic components of soil respiration? Global Change Biology 10:1756-1766. doi:10.1111/j.1365-2486.2004.00816.x.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., and Finnveden, G. 2006. Scenario types and techniques – towards a user's guide. Futures 34:723–739. DOI: 10.1016/j.futures.2005.12.002.

British Columbia Ministry of Forests. 1998. Provincial Seedling – Stock Type Selection and Ordering Guidelines. Retrieved August 2019 from https://www.for.gov.bc.ca/hfd/pubs/docs/sil/sil153.pdf.

Canada Energy Regulator. 2019. Provincial and Territorial Energy Profiles – Saskatchewan. Government of Canada. Retrieved August 2019 from https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/nrgsstmprfls/sk-eng.html.

Caterpillar. 2019. Skid Steer Loaders. Retrieved from https://www.cat.com/en_US/products/new/equipment/skid-steer-loaders.html.

Center-for-Urban-Forest-Research. 2008. CUFRTree Carbon Calculator. Retrieved from http://www.fs.fed.us/ccrc/topics/urban-forests/ctcc/.

Clean Energy Canada. 2016. Reducing GHG Emissions in Canada's Transportation Sector. Submission to the Mitigation Measures Working Group - Pan-Canadian Framework on Climate Change and Clean Growth. Retrieved September 2019 at http://equiterre.org/sites/fichiers/fmm_transportation_recs.pdf.

CORRIM Inc. 2004. Phase I research report on the research plan to develop environmental-performance measures for renewable building materials with alternatives for improved performance. Seattle, WA.

CPM, 2007. SPINE@CPM database. Competence Center in Environmental Assessment of Product and Material Systems (CPM), Chalmers University of Technology, Göteborg.

Curran, M.A., Mann, M., Norris, G., 2005. The international workshop on electricity data for life cycle inventories. Journal of Cleaner Production 13(8):853–862. DOI: 10.1016/j.jclepro.2002.03.001.

Davis, E.L., Laroque, C.P., and Van Rees, K., 2013. Evaluating the suitability of nine shelterbelt species for dendrochronological purposes in the Canadian Prairies. Agroforestry Systems 87:713-727.

Department of the Environment and Energy. 2014. Repealing the Carbon Tax. Government of Australia. Retrieved June 2017 from https://www.environment.gov.au/climate-change/publications/factsheet-repeal-carbon-tax-treatment-sggs.

Department of the Environment and Energy. 2017a. Review of Climate Change Policies. Government of Australia. Retrieved June 2017 from http://www.environment.gov.au/system/files/pages/64722841-01ab-4067-a978-40d63174d4c7/files/tor-climate-change-review.pdf.

Department of the Environment and Energy. 2017b. Emissions Reduction Fund. Government of Australia. Retrieved June 2017 from http://www.environment.gov.au/climate-change/government/emissions-reduction-fund.

Dobb, A. 2013. BC Farm Practices & Climate Change Adaptation – Shelterbelts. Climate Action Initiative – BC Agriculture & Food. Retrieved July 10 2019 from https://www.bcagclimateaction.ca/wp/wp-content/media/FarmPractices-Shelterbelts.pdf.

Ecoinvent, n.d. Ecoinvent version 3.5. Ecoinvent, Technoparkstrasse 1. Retrieved July 15 2019 from https://www.ecoinvent.org/home.html.

Ecoinvent. 2007. Swiss Centre for Life Cycle Inventories (Ecoinvent Centre). Ecoinvent Database. Ecoinvent Centre, Dübendorf, 2004 and 2007. Retrieved from http://www.ecoinvent.org.

Ekvall T., and Weidema B. P. 2004. System boundaries and input data in consequential life cycle inventory analysis. International Journal of Life Cycle Assessment 9(3):161–71. DOI: 10.1065/lca2004.03.148.

Environment and Climate Change Canada. 2018. National Inventory Report, 1990-2016. Retrieved August 2019 at https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/emissions-inventories-reporting/nir-executive-summary/National%20Inventory%20Report%20Executive%20Summary%202018.pdf.

Esau, R. 2007. Weed Control for Alberta Shelterbelts. Agri-Facts. Albert Agriculture and Food. Revised by Spencer, R and Chrapko, D. Retrieved December 2 2019 from https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex977/$file/277_645-1.pdf?OpenElement.

European Commission. 2007. European Commission, Directorate General Joint Research Centre (JRC), European Reference Life Cycle Database (ELCD). Retrieved from http://lca.jrc.ec.europa.eu/lcainfohub/.

Farm Stewardship Program. 2016. Shelterbelt Establishment BMP. Retrieved from http://publications.gov.sk.ca/documents/20/89072-Shelterbelt%20Establishment%20BMP%20Guidelines%20-%20September%2023,%202016.pdf.

Finnveden, G, Hauschild, M. Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., and Suh, S. 2009. Recent Developments in Life Cycle Assessment. Journal of Environmental Management 91(1):1-21.

Frischknecht, R., and Jungbluth, N. (editors). 2007. Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, Switzerland.

Google Maps. 2019. Retrieved June 2018 from https://www.google.com/maps.

Government of Alberta. 2007. Field Shelterbelts for Soil Conservation. Agri-Facts. Retrieved May 25 2019 from https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex2073/$file/277_20-3.pdf?OpenElement.

Government of Alberta. 2017a. Output-based Allocation System Engagement. Retrieved June 2017 from https://www.alberta.ca/output-based-allocation-engagement.aspx.

Government of Alberta. 2017b. Carbon levy and rebates. Retrieved June 2017 from https://www.alberta.ca/climate-carbon-pricing.aspx.

Government of California. 2017a. California Carbon Capture and Storage. California Climate Change. Retrieved June 2017 from http://www.climatechange.ca.gov/carbon_capture_review_panel/.

Government of California. 2017b. Low Carbon Fuel Standard. California Air Resources Board. Retrieved June 2017 from https://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

Government of Canada. 2017a. The Pan-Canadian Framework on Clean Growth and Climate Change. Retrieved June 2017 from https://www.canada.ca/en/services/environment/weather/climatechange/pan-canadian-framework.html.

Government of Canada. 2018. National Inventory Report 1990-2017: Greenhouse Gas Sources and Sinks in Canada. Annex 6. Retrieved August 2017 from https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/emissions-inventories-reporting/nir-executive-summary/National%20Inventory%20Report%20Executive%20Summary%202018.pdf.

Government of Canada. 2019a. Tree mortality. Natural Resources Canada. Retrieved on July 5, 2019 at https://www.nrcan.gc.ca/forests/topics/climate-change/forest-change-indicators/tree-mortality/17785.

Government of Canada. 2019b. Fiscal and Distributional Analysis of the Federal Carbon Pricing System. Office of the Parliament Budget Officer. Retrieved August 2019 at www.pbo-dpb.gc.ca.

Government of Canada. 2019c. Line 449 – Climate action incentive. Retrieved August 2019 from https://www.canada.ca/en/revenue-agency/services/tax/individuals/topics/about-your-tax-return/tax-return/completing-a-tax-return/deductions-credits-expenses/line-449-climate-action-incentive.html.

Government of Manitoba. 2018. Manitoba Rejects Carbon Tax, Moves Ahead With Made-In-Manitoba Climate and Green Plan. Retrieved from August 2019 https://news.gov.mb.ca/news/index.html?item=44667&posted=2018-10-03.

Government of Manitoba. 2019. Manitoba to Challenge Ottawa's Carbon Tax in Court. Retrieved September 2019 from https://news.gov.mb.ca/news/index. html?item=45161&posted=2019-04-03. 53.

Government of Ontario. 2017. Cap and trade in Ontario. Retrieved June 2017 from https://www.ontario.ca/page/cap-and-trade-ontario.

Government of Saskatchewan. 2017. Beneficial Management Practices Guidelines. Retrieved July 2017 from https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/growing-forward-2/environment-programs/farm-stewardship-program/beneficial-management-practices.

Government of Saskatchewan. 2018. Province Challenging Federal Government's Ability to Impose a Carbon Tax. Retrieved October 2018 from https://www.saskatchewan.ca/ government/news-and-media/2018/april/25/carbon-tax-case.

Growing Forward 2. 2016. Growing Forward Farm Stewardship Program (FSP). Retrieved June 2017 from http://www.nsrbc.ca/mrws/filedriver/FSP_Poster_May2016_Updated.pdf.

Heidinger, S. June 2018. Personal interview (email). Hesselink, B. June 2018. Personal interview (phone and email).

Hunkeler, D., and Rebitzer, G., 2005. The future of life cycle assessment. International Journal of Life Cycle Assessment 10:305–308. DOI: 10.1065/lca2005.09.001.

ICF Consulting Canada. 2017. Long-Term Carbon Price Forecast Report. ICF Consulting Canada, Inc, Toronto. Retrieved June 2017 from https://www.oeb.ca/sites/default/files/uploads/OEB-LTCPF-Report-20170531.pdf.

Ingram, D. L. 2012. Life cycle assessment of a field-grown red maple tree to estimate its carbon footprint components. International Journal of Life Cycle Assessment 17:453-462.

International Organization for Standardization (ISO), 2006. ISO 14040 International Standard. In: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

Jay's Transport Group. April 2018. Personal communication (email).

JEMAI. 2007. Japan Environmental Management Association for Industry (JEMAI). JEMAI database. Retrieved June 2017 from http://www.jemai.or.jp/english/index.cfm.

Kendall, A., and McPherson, E.G. 2011. A life cycle greenhouse gas inventory of a tree production system. International Journal Life Cycle Assessment 17(4):444–452.

Kort, J. 1988. 9. Benefits of Windbreaks to Field and Forage Crops. Agriculture, Ecosystems and Environment 22/23:165–190.

Kort, J., and Turnock, R. 1999. Carbon reservoir and biomass in Canadian prairie shelterbelts. Agroforestry Systems 44:175–186.

Lal, R. 2004. Carbon emissions from farm operations. Environment International 30:981–990.

Laroque, C. July 2019. Personal communication.

Lave, L.B., Cobras-Flores, E., Hendrickson, C., and McMichael, F. 1995. Using input– output analysis to estimate economy wide discharges. Environmental Science Technology 29:420–426. DOI: 10.1021/es00009a003.

Lenzen, M. 2000. Errors in conventional and input–output-based life-cycle inventories. Journal of Industrial Ecology 4:127–148. DOI: 10.1162/10881980052541981.

Master Plant-Prod Inc. 2019. Plant-Prod 20-8-20 All Purpose High Nitrate. High Productivity Plant Nutrition. Retrieved May 17 2019 from https://www.plantprod.com/product/plant-prod-20-8-20-all-purpose-high-nitrate/.

Meng, S., Siriwardana, M., and McNeill, J. 2012. The Environmental and Economic Impact of the Carbon Tax in Australia. Environmental and Resource Economics 54(3):313–332. DOI: 10.1007/s10640-012-9600-4.

Moriguchi, Y., Kondo, Y., and Shimizu, H. 1993. Analyzing the life cycle impact of cars: the case of CO2. Industrial Environment 16(1–2):42–45.

Murray, B., and Rivers, N. 2015. British Columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy". Energy Policy 8:674–683. DOI: 10.1016/j.enpol.2015.08.011.

Narita, N., Nakahara, Y., Morimoto, M., Aoki, R., and Suda, S. 2004. Current LCA database development in Japan–results of the LCA project. International Journal of Life Cycle Assessment 9:355–359. DOI: 10.1065/lca2004.09.180.3.

National Renewable Energy Laboratory (NREL). 2004. US Life Cycle Inventory Database. NREL, Golden, CO. Retrieved from http://www.nrel.gov/lci/.

Natural Resources Canada. 2019. Energy and Greenhouse Gases (GHGs) Emissions. Retrieved from https://www.nrcan.gc.ca/energy-and-greenhouse-gas-emissions-ghgs/20063.

Nemecek, T., Dubois, D., Gunst, L., and Gaillard, G. 2005. Life cycle assessment of conventional and organic farming in the DOC trial. In: Researching sustainable systems. Proceedings of the First Scientific Conference of the International Society of Organic Agriculture Research (ISOFAR), held in Cooperation with the International Federation of Organic Agriculture Movements (IFOAM) and the National Association for Sustainable Agriculture, Australia (NASAA), Adelaide Convention Centre, Adelaide, South Australia, 21-23 September. ISBN 3-906081-76-1, pp 222-226.

O'Connor, J. 2004. Survey on actual service lives for North American buildings. Presented at Woodframe Housing Durability and Disaster Issues conference, Las Vegas. Retrieved September 2019 at https://cwc.ca/wp-content/uploads/2013/12/DurabilityService_Life_E.pdf.

Office of Energy Efficiency & Renewable Energy. 2010. Fact #621: May 3, 2010 Gross Vehicle Weight vs. Empty Vehicle Weight. Retrieved May 2018 from https://www.energy.gov/eere/vehicles/fact-621-may-3-2010-gross-vehicle-weight-vs-empty-vehicle-weight.

Office of Energy Efficiency & Renewable Energy. 2012. Ford F150 Pickup. Fuel economy. Retrieved May 2018 from https://www.fueleconomy.gov/feg/bymodel/2012_Ford_F150_Pickup.shtml.

Ontario Ministry of Natural Resources and Forestry. 2019. Managed Forest Tax Incentive Program. Government of Ontario. Retrieved Nov 10 2019 at https://www.ontario.ca/page/managed-forest-tax-incentive-program.

Ontl, T., and Shulte, L. 2012. Soil Carbon Storage. Nature Education Knowledge 3(10):35.

Pisupati, S. 2018. Energy Conservation and Environmental Protection. EGEE 102 Module. Penn State College of Earth and Mineral Sciences, Pennsylvania, USA.

Pré. Guinée, J., et al. (Various authors). 2019. SimaPro Database Manual. Methods Library.

Rajagopal, D. 2014. Consequential life cycle assessment of policy vulnerability to price effects. Journal of Industrial Ecology 18(2):164–75. DOI: 10.1111/jiec.12058.

Rajagopal, D., Vanderghem, C., and MacLean, L. 2017. Life Cycle Assessment for Economists. Annual Review of Resource Economics 9:361—381. DOI: https://doi.org/10.1146/annurev-resource-100815-095513.

Rempel, J. 2014. Costs, Benefits, and Barriers to the Adoption and Retention of Shelterbelts in Prairie Agriculture as identified by Saskatchewan Producers (MES thesis). University of Saskatchewan, Saskatoon, Saskatchewan.

Rivers, N. J., and Schaufele, B. 2015. The effect of carbon taxes on agricultural trade. Canadian Journal of Agricultural Economics 63(2):235—257. DOI: 10.1111/cjag.12048.

Rostami, A., Shasavar, A. 2009. Effects of Seed Scarification on Seed Germination and Early Growth of Olive Seedlings. Journal of Biological Sciences 9:825-828.

Ryan, J. 2014. New Study Verifies Steel Roofs Can Last As Long As The Buildings They Cover: Typically 60 Years or More. Tag Archives: Life Expectancy. Metal Construction. Retrieved September 2019 from https://blog.metalconstruction.org/tag/life-expectancy/.

Saskatchewan Gazette. 2018. The Management and Reduction of Greenhouse Gases (Standards and Compliance) Regulations, December 14, 2018. Retrieved September 2019 from http://www.publications.gov.sk.ca/freelaw/documents/English/Regulations/Regulations/M2-01R3.pdf.

SaskPower. 2019a. Apply for free seedlings. Retrieved July 2019 from https://www.SaskPower.com/accounts-and-services/service-requests/other-services/apply-for-free-seedlings.

SaskPower. 2019b. Shand Greenhouse. Retrieved January 2019 from https://www.SaskPower.com/Our-Power-Future/Our-Environmental-Commitment/Shand-Greenhouse.

Schlesinger, W.H., and Andrews, J.A. 2000. Soil respiration and the global carbon cycle. Biogeochemistry 48:7. https://doi.org/10.1023/A:1006247623877.

Seely, A., and Ares, E. 2016. Briefing Paper - Climate Change Levy: renewable energy & the carbon reduction commitment. House of Commons Library. Retrieved from http://researchbriefings.files.parliament.uk/documents/CBP-7283/CBP-7283.pdf.

Shelterbelt Solutions. June 2019. Personal communication (email).

Sheth, K. 2017. Windbreaks and Shelterbelts: Wind Erosion Control in Farming. Economics. Retrieved July 2 2019 at https://www.worldatlas.com/articles/windbreaks-and-shelterbelts-wind-erosion-control-in-farming.html.

SimaPro. 2019. About SimaPro. Retrieved February 2018 from https://simapro.com/about/.

South Coast Air Quality Management District (SCAQMD). 2008. Interim CEQA GHG Significance Threshold for Stationary Sources, Rules and Plans. Retrieved August 2019 from http://www.aqmd.gov/docs/default-source/ceqa/handbook/greenhouse-gases-(ghg)-ceqa-significance-thresholds/ghgboardsynopsis.pdf?sfvrsn=2.

Strazza, C., Borghi, A. D., and Gallo, M. 2013. Development of Specific Rules for the Application of Life Cycle Assessment to Carbon Capture and Storage. Energies 6:1250—1265. DOI: 10.3390/en6031250.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., and Norris, G. 2004. System boundary selection in life-cycle inventories using hybrid approaches. Environmental Science and Technology 38:657–664. DOI: 10.1021/es0263754.

The Morton Arboretum. 2019. Fertilizing. TREES & plants. Retrieved June 2019 from https://www.mortonarb.org/trees-plants/tree-and-plant-advice/horticulture-care/fertilizing.

The Royal Melbourne Institute of Technology (RMIT). 2007. Centre for Design, RMIT University. Australian LCI Database. Retrieved June 2017 from http://www.auslci.com/.

UBA, 2007. Umweltbundesamt (UBA) (German Environmental Protection Agency). PROBAS Database. Retrieved June 2017 from http://www.probas.umweltbundesamt.de/php/index.php.

United States Department of Agriculture (USDA). Glossary of Landform and Geological Terms – NRCS. Retrieved December 2019 from https://www.nrcs.usda.gov/.

United States Geological Survey (USGS). 1988. Rain and Precipitation. Retrieved May 2018 from https://www.usgs.gov/special-topic/water-science-school/science/rain-and-precipitation?qt-science_center_objects=0#qt-science_center_objects.

US Department of Energy (USDOE). 1998. Method of calculating carbon sequestration by trees in urban and suburban settings. United States Department of Energy (DOE): p. 15. Retrieved May 2018 from ftp://ftp.eia.doe.gov/pub/oiaf/ 1605/cdrom/pdf/sequester.pdf.

Valentine, H.T., Tritton, L.M., and Furnival, G.M. 1984. Subsampling trees for biomass volume, or mineral content. Science 30:673-681.

Watson, R.T., Rodhe, H., and Oeschger, H. 1990. Greenhouse gases and aerosols. Climate Change: The IPCC Scientific Assessment. Cambridge University Press, Cambridge, United Kingdom.

Weather Atlas. 2019. Monthly weather forecast and Climate Estevan, Canada. Retrieved May 2018 from https://www.weather-ca.com/en/canada/estevan-climate.

Weidema, B.P., Ekvall, T., Pesonen, H. L., Rebitzer, G., Sonneman, G.W., and Spielmann, M. 2004. Scenarios in LCA. SETAC, Brussels.

Wiseman G., Kort J., and Walker, D. 2009. Quantification of Shelterbelt Characteristics Using High-Resolution Imagery, Agriculture, Ecosystems and Environment 131:111–117.

World Bank Group. 2016. State and Trends of Carbon Pricing. Climate Change. Retrieved from http://documents.worldbank.org/curated/en/598811476464765822/pdf/109157-REVISED-PUBLIC-wb-report-2016-complete-161214-cc2015-screen.pdf.

World Bank Group. 2019. States and Trends of Carbon Pricing. Retrieved from http://www.worldbank.org/content/dam/Worldbank/Highlights%20&%20Features/Climate%20Change/carbon-pricing-map-900x476-c.jpg.

Zilberman, D., Zhao J., and Heiman A. 2012. Adoption versus adaptation, with emphasis on climate change. Annual Review of Resource Economics 4:27–53. DOI: 10.1146/annurev-resource-083110-115954**.**

Appendix A - Inputs used for Production of Seedlings

Table A.1 – List with Dosage of Inputs for the Production of Seedlings at Shand Greenhouse with Data Proxies

Input		Annual amount	Unit	Proxy Data
Chemicals	Avid (Insecticide)	22.5	ml	Insecticide, at plant/RER[10] Energy
	Citation (Insecticide)	300	g	Insecticide, at plant/RER Energy
	Dipel (Bioinsecticide)	285	g	Insecticide, at plant/RER Energy
	Dynomite (Insecticide)	72	g	Insecticide, at plant/RER Energy
	Enstar (Insecticide)	6	ml	Insecticide, at plant/RER Energy
	Intercept (Insecticide)	98.4	g	Insecticide, at plant/RER Energy
	Maestro (Fungicide)	8170	g	Fungicide, at plant/RER Energy
	Pylon (Insecticide)	450	ml	Insecticide, at plant/RER Energy
	Round-Up Weather Maxx	6	L	Glyphosate {GLO[11]}|market
	Senator (Fungicide)	7400	g	Fungicide, at plant/RER Energy
	Trounce (Insecticide)	4200	ml	Insecticide, at plant/RER Energy
	Truban (Fungicide)	543	ml	Fungicide, at plant/RER Energy
	Zerotol (Fungicide)	10.46	L	Acetic acid, without water, in 98% solution state {RoW[12]}| acetaldehyde oxidation | APOS, U
Energy	Electricity	1, 270, 800	kWh	Electricity, medium voltage {CA-SK}| market for | APOS, U
Equipment	Tractor with fork attachment	1	p	Tractor, 4-wheel, agricultural {RoW}| production | APOS, U
	Truck	1	p	Transport, freight, light commercial vehicle {GLO}| market for | APOS, U

[10] RER: Europe

[11] GLO: Global

[12] RoW: Rest of World

Table A.1 (Cont.)

Fuels	Diesel	86	gal	Diesel {GLO}| market group for | APOS, U
	Gas	600	gal	Gasoline (regular), from crude oil, consumption mix, at refinery, 100 ppm Sulphur EU-15 S System - Copied from ELCD
Infra-structure	Main greenhouse	1	p	Greenhouse, glass walls and roof {GLO}| market for greenhouse, glass walls and roof | APOS, U
	Headerhouse	1	p	Building, hall, steel construction {RoW}| building construction, hall, steel construction | APOS, U
	Shade house	2	p	Building, hall, steel construction {RoW}| building construction, hall, steel construction | APOS, U
	Storage building	2	p	Building, hall, steel construction {RoW}| building construction, hall, steel construction | APOS, U
Irrigation	Irrigation	5.6 x 10^6	L	Irrigation {CA-QC}| irrigation | APOS, U
Material	20-8-20 All Purpose High Nitrate fertilizer	645	kg	Nitrogen fertilizer, as N {GLO}| market for | APOS, U
	Sulphuric acid	1	L	Sulphuric acid {GLO}| market for | APOS, U
	Clorox Bleach	1	L	Sodium hypochlorite, without water, in 15% solution state {GLO}| market for | APOS, U
	Incubators	2	p	Electricity, medium voltage {CA-SK}| market for | APOS, U
	Nylon mesh bags	50	p	Nylon 6-6 {GLO}| market for | APOS, U
	Purified water	50	L	Water, ultrapure {GLO}| market for | APOS, U
	Seeds	4,203,390	p	Tree seedling, for planting {RoW}| tree seedling production, in unheated greenhouse | APOS, U
	Spencer-Lemaire Plastic Trays	2	p	Polystyrene, expandable {GLO}| market for | APOS, U
	Styroblock Containers	8500	p	Polystyrene, expandable {GLO}| market for | APOS, U
	Meat wrap plastic wrap	2.50	g	Packaging film, low density polyethylene {GLO}| market for | APOS, U
	Small plastic bags	1.75	g	Polypropylene, granulate {GLO}| market for | APOS, U
	Large box	1	kg	
	Small box	400	g	

Appendix B - Inputs used for Planting and Maintenance, and Removal of Shelterbelts plus Level of TEC

Table B.1 - Inputs for Planting and Maintenance with Proxy Data

	Inputs from Technosphere	Amount	Unit	Proxy data
Planting	Tillage	1000	m^2	Tillage, rotary cultivator {CA-QC}| tillage, rotary cultivator | APOS, U
	Planting seedlings	277*	p	Planting tree {RoW}| planting tree | APOS, U
Maintenance	Herbicide	3.47	kg	Glyphosate, at plant/RER Energy
	Fertilizer	15	kg	Potassium nitrate {GLO}| market for | APOS, U
	Irrigation	1218709	L	Irrigation {CA-QC}| irrigation | APOS, U
	Tillage	1000	m2	Tillage, rotary cultivator {RoW}| processing | APOS, U

* This value is based on a kilometre long coniferous shelterbelt which would require 277 seedlings based on spacing recommendations by the AAFC (2010). This value differs by type of shelterbelt planted.

Table B.2 - Inputs for Removal with Proxy Data

Inputs from Technosphere	Amount	Unit	Proxy data
Skid-steer loader w/ attachment	805	m^3	Excavation, skid-steer loader {RoW}| processing | APOS, U
Machine Hours	40*	hr	Machine operation, diesel, >= 18.64 kW and < 74.57 kW, low load factor {GLO}| machine operation, diesel, >= 18.64 kW and < 74.57 kW, low load factor | APOS, U

* Number of hours required depends upon on type of shelterbelt being removed. Generally 40 hours is representative to remove a shelterbelt of coniferous and deciduous trees that are medium in size.

Table B.3 - TEC CO_2 in tonnes per km of Species in the Brown Soil zone, Five-Year Increments

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
5	-0.26	0.50	-3.82	1.04	-2.43	-2.64
10	10.47	12.28	10.27	31.54	5.49	-5.77
15	28.81	33.91	59.74	70.67	26.75	-4.16
20	53.91	62.71	138.21	115.15	56.43	16.69
25	85.45	97.89	243.50	163.91	93.81	64.14
30	122.53	137.13	366.84	215.06	135.42	130.57
35	162.12	176.73	497.06	263.69	179.16	190.96
40	210.67	223.69	664.50	320.57	231.08	267.84
45	267.02	275.58	855.41	383.45	288.80	331.82
50	322.76	322.47	1046.96	439.55	344.91	383.63
55	384.69	371.65	1260.68	499.44	407.44	438.42
60	454.88	424.71	1500.49	565.82	477.14	495.79

Table B.4 - TEC CO_2 in Tonnes per Species in the Dark Brown Soil Zone, Five-Year Increments

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
5	-1.30	-0.15	-5.32	0.50	-3.26	-3.96
10	8.30	11.14	7.62	29.97	3.98	-8.71
15	25.14	31.67	55.18	67.80	24.14	-6.85
20	48.63	59.49	131.62	111.22	52.93	18.76
25	78.61	93.92	235.83	159.12	89.69	76.52
30	113.69	131.77	355.57	208.77	129.93	144.38
35	151.48	170.32	483.24	256.35	172.66	213.34
40	198.61	216.77	649.27	312.89	224.08	303.31
45	253.61	268.35	840.07	375.52	281.74	378.42
50	308.48	315.35	1033.83	431.83	338.76	440.89
55	370.11	365.18	1251.55	492.71	403.07	507.85
60	436.92	415.70	1482.80	556.01	470.29	572.01

Table B.5 – Cumulative TEC CO_2 km in Tonnes by Species in the Black Soil Zone, Five-Year Increments

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
5	-2.13	-0.64	-6.43	0.01	-4.05	-3.90
10	6.03	10.04	5.18	27.11	3.49	-8.53
15	21.15	29.57	50.59	63.49	23.68	-6.78
20	42.53	56.11	123.78	105.48	52.50	15.46
25	70.05	89.21	224.33	151.96	89.50	65.33
30	102.26	125.40	339.69	199.71	129.95	130.00
35	137.62	163.11	464.71	246.49	173.50	191.47
40	182.08	208.76	627.60	302.18	225.83	270.47
45	234.13	259.52	815.00	363.87	284.68	336.36
50	286.07	305.87	1006.03	419.30	343.30	391.06
55	345.49	356.08	1224.67	480.47	411.02	451.10
60	410.71	407.51	1461.39	544.80	483.67	510.58

Table B.6 – Cumulative TEC CO_2 in Tonnes per km of Species in the Dark Brown Soil Zone, for the First 25 Years

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
1	-4.68	-1.66	-1.66	-1.66	-2.18	-2.18
2	-5.62	-2.32	-3.44	-2.29	-2.99	-2.84
3	-6.01	-2.28	-5.02	-2.91	-3.76	-3.50
4	-5.53	-1.87	-6.32	-3.03	-4.36	-4.16
5	-4.94	-1.16	-6.98	-0.62	-4.61	-4.82
6	-3.59	0.13	-7.30	4.05	-4.62	-5.47
7	-1.84	1.91	-6.27	9.39	-3.84	-6.12
8	0.18	4.10	-4.32	15.13	-2.33	-6.77
9	2.69	6.96	-0.36	22.02	0.04	-7.38
10	5.80	10.62	5.96	29.88	3.31	-7.95
11	8.93	14.38	13.03	37.31	6.83	-8.40
12	12.33	18.39	21.43	44.92	10.70	-8.65
13	16.09	22.80	31.25	52.91	14.91	-8.52
14	19.87	27.22	41.17	60.61	19.33	-7.87
15	24.13	32.25	53.52	69.01	24.58	-6.34
16	28.49	37.38	66.56	77.28	29.77	-4.05
17	33.39	43.04	80.67	86.23	35.48	-0.86
18	38.47	48.85	96.56	95.24	41.49	3.30
19	43.69	54.81	112.91	104.21	47.64	8.34
20	49.23	61.05	129.96	113.49	54.25	14.51
21	54.87	67.45	148.35	122.64	61.03	21.71
22	60.89	74.23	168.02	132.21	68.32	30.14
23	67.60	81.73	190.18	142.68	76.12	39.88
24	74.12	88.98	212.76	152.49	84.04	50.76
25	80.77	96.23	234.17	162.25	91.63	61.96

Table B.7 – Cumulative TEC CO_2 in Tonnes per km of Species in the Dark Brown Soil Zone, for the First 25 Years

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
1	0.00	0.00	0.00	0.00	0.00	0.00
2	-0.33	-0.23	-0.49	-0.22	-0.28	-0.27
3	-0.50	-0.27	-0.92	-0.44	-0.55	-0.54
4	-0.44	-0.21	-1.27	-0.52	-0.78	-0.81
5	-1.30	-0.15	-5.32	0.50	-3.26	-3.96
6	-0.05	0.26	-1.54	1.35	-0.95	-1.35
7	0.37	0.74	-1.26	2.77	-0.77	-1.62
8	0.83	1.27	-0.72	4.17	-0.41	-1.88
9	1.47	2.03	0.35	6.04	0.21	-2.14
10	8.30	11.14	7.62	29.97	3.98	-8.71
11	3.05	4.01	4.01	10.14	2.01	-2.55
12	3.90	5.05	6.30	12.13	3.00	-2.66
13	4.84	6.20	8.98	14.24	4.08	-2.64
14	5.77	7.31	11.68	16.24	5.18	-2.43
15	25.14	31.67	55.18	67.80	24.14	-6.85
16	7.96	9.98	18.61	20.68	7.95	-1.09
17	9.17	11.42	22.46	23.00	9.41	-0.04
18	10.50	13.00	26.79	25.46	11.05	1.40
19	11.85	14.59	31.25	27.87	12.70	3.10
20	48.63	59.49	131.62	111.22	52.93	18.76
21	14.71	17.92	40.91	32.77	16.25	7.51
22	16.28	19.73	46.28	35.36	18.21	10.31
23	18.04	21.76	52.32	38.20	20.30	13.54
24	19.76	23.74	58.48	40.88	22.48	17.23
25	78.61	93.92	235.83	159.12	89.69	76.52

Table B.8 – Cumulative TEC CO_2 in Tonnes per km of Species in the Black Soil Zone, for the First 25 Years

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
1	0.00	0.00	0.00	0.00	0.00	0.00
2	-0.38	-0.27	-0.56	-0.25	-0.33	-0.27
3	-0.61	-0.29	-1.07	-0.50	-0.64	-0.53
4	-0.61	-0.31	-1.50	-0.62	-0.90	-0.80
5	-2.13	-0.64	-6.43	0.01	-4.05	-3.90
6	-0.33	0.11	-1.90	1.12	-1.11	-1.33
7	0.00	0.54	-1.70	2.39	-0.93	-1.59
8	0.36	1.02	-1.27	3.59	-0.57	-1.85
9	0.91	1.75	-0.28	5.30	0.04	-2.10
10	6.03	10.04	5.18	27.11	3.49	-8.53
11	2.35	3.68	3.27	9.29	1.89	-2.51
12	3.08	4.63	5.41	11.15	2.84	-2.62
13	3.95	5.74	8.02	13.22	3.96	-2.58
14	4.80	6.80	10.60	15.16	5.05	-2.37
15	21.15	29.57	50.59	63.49	23.68	-6.78
16	6.77	9.34	17.17	19.43	7.81	-1.17
17	7.88	10.73	20.92	21.70	9.31	-0.23
18	9.09	12.24	25.06	24.08	10.94	1.01
19	10.30	13.73	29.27	26.37	12.55	2.45
20	42.53	56.11	123.78	105.48	52.50	15.46
21	12.90	16.90	38.51	31.09	16.12	6.27
22	14.33	18.62	43.61	33.58	18.07	8.66
23	15.97	20.60	49.53	36.38	20.20	11.46
24	17.58	22.55	55.58	39.03	22.43	14.69
25	70.05	89.21	224.33	151.96	89.50	65.33

Table B.9 - DOM CO_2 Loss over 100 Years Following the Removal of Shelterbelts by Species over Five-Year Increments for the Brown Soil Zone

Years following removal	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
0	429.23	314.26	717.68	359.96	316.05	305.96
5	424.53	310.96	710.71	356.83	311.98	302.65
10	419.82	307.66	703.75	353.69	307.92	299.34
15	415.12	304.36	696.79	350.56	303.85	296.02
20	410.41	301.06	689.82	347.42	299.78	292.71
25	405.71	297.76	682.86	344.29	295.71	289.40
30	401.01	294.46	675.90	341.15	291.65	286.09
35	396.30	291.16	668.93	338.02	287.58	282.78
40	391.60	287.86	661.97	334.89	283.51	279.46
45	386.89	284.56	655.01	331.75	279.44	276.15
50	382.19	281.25	648.04	328.62	275.38	272.84
55	377.48	277.95	641.08	325.49	271.31	269.53
60	372.78	274.65	634.12	322.35	267.24	266.21
65	368.07	271.35	627.15	319.22	263.18	262.90
70	363.37	268.05	620.19	316.09	259.11	259.59
75	358.67	264.75	613.22	312.95	255.04	256.28
80	353.96	261.45	606.26	309.82	250.97	252.97
85	349.26	258.15	599.30	306.68	246.91	249.66
90	344.56	254.85	592.34	303.55	242.84	246.35
95	339.85	251.55	585.37	300.41	238.77	243.03
100	335.15	248.25	578.41	297.28	234.70	239.72

Table B.10 - DOM CO_2 Loss over 100 Years Following the Removal of Shelterbelts by Species over Five-Year Increments for the Dark Brown Soil Zone

Years following removal	**Caragana**	**Green ash**	**Hybrid poplar**	**Manitoba maple**	**Scots pine**	**White spruce**
0	494.13	361.32	818.15	404.62	374.32	365.06
5	488.12	357.10	809.25	400.61	369.12	360.08
10	482.10	352.88	800.35	396.61	363.92	355.10
15	476.09	348.66	791.45	392.60	358.72	350.12
20	470.08	344.44	782.54	388.59	353.53	345.14
25	464.06	340.22	773.64	384.59	348.33	340.16
30	458.05	336.00	764.74	380.58	343.13	335.18
35	452.04	331.78	755.84	376.57	337.93	330.20
40	446.02	327.57	746.94	372.57	332.73	325.22
45	440.01	323.35	738.04	368.56	327.53	320.24
50	434.00	319.12	729.14	364.55	322.33	315.26
55	427.98	314.91	720.24	360.55	317.13	310.27
60	421.97	310.69	711.34	356.54	311.93	305.29
65	415.96	306.47	702.43	352.54	306.74	300.31
70	409.94	302.25	693.54	348.53	301.54	295.33
75	403.93	298.03	684.63	344.52	296.34	290.35
80	397.92	293.81	675.73	340.52	291.14	285.37
85	391.90	289.59	666.83	336.51	285.94	280.39
90	385.89	285.37	657.93	332.50	280.74	275.41
95	379.88	281.15	649.03	328.50	275.54	270.43
100	373.86	276.93	640.13	324.49	270.34	265.45

Table B.11 - DOM CO_2 Loss over 100 Years Following the Removal of Shelterbelts by Species over Five-Year Increments for the Black Soil Zone

Years following removal	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
0	536.49	395.35	889.31	436.38	420.16	408.01
5	529.53	390.47	879.01	431.74	414.14	403.11
10	522.57	385.58	868.71	427.10	408.13	398.21
15	515.61	380.70	858.41	422.47	402.11	393.31
20	508.65	375.82	848.11	417.83	396.09	388.41
25	501.69	370.93	837.80	413.19	390.07	383.51
30	494.73	366.05	827.50	408.55	384.05	378.61
35	487.77	361.17	817.20	403.92	378.04	373.71
40	480.81	356.29	806.90	399.28	372.02	368.81
45	473.85	351.40	796.60	394.65	366.00	363.91
50	466.89	346.52	786.29	390.01	359.99	359.01
55	459.93	341.63	776.00	385.37	353.97	354.11
60	452.97	336.75	765.69	380.74	347.95	349.21
65	446.01	331.87	755.39	376.10	341.94	344.31
70	439.05	326.99	745.09	371.46	335.92	339.41
75	432.09	322.10	734.79	366.83	329.90	334.51
80	425.13	317.22	724.49	362.19	323.88	329.61
85	418.17	312.34	714.18	357.56	317.86	324.71
90	411.21	307.45	703.88	352.92	311.85	319.81
95	404.25	302.57	693.58	348.28	305.83	314.91
100	397.29	297.69	683.28	343.64	299.81	310.01

Appendix C - Cumulative Carbon Sequestration in Five-Year Increments

Table C.1 – Cumulative CO_2 Sequestration in Tonnes in Five-Year Increments for the Brown Soil Zone

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
1	0.00	0.00	0.00	0.00	0.00	0.00
5	-0.26	0.50	-3.82	1.04	-2.43	-2.64
10	10.47	12.28	10.27	31.54	5.49	-5.77
15	28.81	33.91	59.74	70.67	26.75	-4.16
20	53.91	62.71	138.21	115.15	56.43	16.69
25	85.45	97.89	243.50	163.91	93.81	64.14
30	122.53	137.13	366.84	215.06	135.42	130.57
35	162.12	176.73	497.06	263.69	179.16	190.96
40	210.67	223.69	664.50	320.57	231.08	267.84
45	267.02	275.58	855.41	383.45	288.80	331.82
50	322.76	322.47	1046.96	439.55	344.91	383.63
55	384.69	371.65	1260.68	499.44	407.44	438.42
60	454.88	424.71	1500.49	565.82	477.14	495.79

Table C.2 - Cumulative CO_2 Sequestration in Tonnes in Five-Year Increments for the Dark Brown Soil Zone

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
5	-1.30	-0.15	-5.32	0.50	-3.26	-3.96
10	8.30	11.14	7.62	29.97	3.98	-8.71
15	25.14	31.67	55.18	67.80	24.14	-6.85
20	48.63	59.49	131.62	111.22	52.93	18.76
25	78.61	93.92	235.83	159.12	89.69	76.52
30	113.69	131.77	355.57	208.77	129.93	144.38
35	151.48	170.32	483.24	256.35	172.66	213.34
40	198.61	216.77	649.27	312.89	224.08	303.31
45	253.61	268.35	840.07	375.52	281.74	378.42
50	308.48	315.35	1033.83	431.83	338.76	440.89
55	370.11	365.18	1251.55	492.71	403.07	507.85
60	436.92	415.70	1482.80	556.01	470.29	572.01

Table C.3 – Cumulative CO_2 Sequestration in Tonnes in Five-Year Increments for the Black Soil Zone

Age	Caragana	Green ash	Hybrid poplar	Manitoba maple	Scots pine	White spruce
5	-2.13	-0.64	-6.43	0.01	-4.05	-3.90
10	6.03	10.04	5.18	27.11	3.49	-8.53
15	21.15	29.57	50.59	63.49	23.68	-6.78
20	42.53	56.11	123.78	105.48	52.50	15.46
25	70.05	89.21	224.33	151.96	89.50	65.33
30	102.26	125.40	339.69	199.71	129.95	130.00
35	137.62	163.11	464.71	246.49	173.50	191.47
40	182.08	208.76	627.60	302.18	225.83	270.47
45	234.13	259.52	815.00	363.87	284.68	336.36
50	286.07	305.87	1006.03	419.30	343.30	391.06
55	345.49	356.08	1224.67	480.47	411.02	451.10
60	410.71	407.51	1461.39	544.80	483.67	510.58